A Critical Review of the Extrusion-based 3D Construction Printing (3DCP) Technology in the Construction Industry

Jinho Ahn[1], Jongjin Park[2] and Hanjong Jun[3]

[1]Adjunct Professor, Department of Architectural Engineering, Hanyang University, Korea
[2]Research Assistant Professor, Department of Architecture, Hanyang University, Korea
[3]Professor, Department of Architecture, Hanyang University, Korea

Abstract

3D printing techniques (also known as additive manufacturing) are maturing and gaining global attentions as an alternative means for full-scale fabrication within the construction industry to increase customization, reduce construction time, and improve affordability. Although there has been significant effort invested over the last two decades in the development of scaled-up 3D construction printing (3DCP) techniques, such as Contour Crafting, D-Shape and Concrete Printing, most of them are based on the extrusion-based processing and there are currently few examples of how such advances could be achieved at a building scale.

The issues that caused decisive restrictions on actively adopting the extrusion-based 3DCP techniques within the construction industry are related to: insufficient material performance, implementation of reinforcement, insufficient qualities in surface finishes and rheology control of cementitious materials. It is therefore necessary to review characteristics and challenges of current extrusion-based 3DCP techniques and explore the potential of other 3D printing technologies for better utilization of the technology in the construction industry in the future. The main purpose of this research is to increase our understanding of explicit limitations of 3DCP techniques based on extrusion process and open up the future opportunities for a more efficient and stable 3DCP system.

Keywords: additive manufacturing; 3D construction printing (3DCP); extrusion-based 3D printing

1. Introduction

3D printing, also known as additive manufacturing (AM), is a rapidly growing technique implemented in various fields. Worldwide revenue consisting of all 3D printing products and services grew by 21% to $7.336 billion in 2017. Hundreds of both large and small companies including Airbus, Adidas, Ford and Toyota are investing billions of dollars in 3D printing R&D (McCue, 2018).

The American Society for Testing and Materials (ASTM) defines 3D printing as “the process for joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies” (ISO/ASTM52900-15, 2015). Over the last two centuries, implementation of 3D printing in the architecture, engineering and construction (AEC) domain has been evolved. There were a few attempts that demonstrated the applicability and potential of the technologies to produce construction components. For example, fused deposition modelling (FDM) and stereolithography apparatus (SLA) were used to produce both geometrically simple and complicated architectural models (Gibson et al., 2002). Medium- or large-scale building models could also be printed using large-scale 3D printers, such as Contour Crafting (Khoshnevis, 2004), D-Shape (Dini, 2008) and Concrete Printing (Lim et al., 2009).

From the construction point of view, 3D printing techniques are gaining global attentions as an alternative means for full-scale fabrication within the construction industry to increase customization, reduce construction cost and time, and improve affordability. However, it should be noted that it is still an emerging technology confronting diverse significant challenges. A critical review of the current development of 3D printing in the construction industry is therefore needed. This paper aims to (1) review the trends and characteristics of 3D printing available in construction in terms of processes and materials used, (2) discuss related methods and challenges of implementing extrusion-based 3D printing, and (3) identifies potential applications and research needs of other 3D printing techniques to better understand what has been done so far and what needs to be done in the future.

Contact Author: Jongjin Park, Research Assistant Professor, Hanyang university, Korea,

e-mail: johnny.jjpark@gmail.com

Table 1. Overview of types of 3D printing technologies

Technology	Type	Material	Cost[1]	Tolerance	Tensile Strength	Speed[2]	Typical Volume[3]
Material Extrusion	**FDM**	Polymer	Low	< 500um	Varies	Moderate	900 x 600 x 900
Vat Photopolymerization	**SLA**	Polymer	Low	< 10um	Moderate (30~85Mpa)	Moderate	1500 x 750 x 500
	DLP	Polymer	Low	< 100um	Moderate (30~85Mpa)	Fast	145 x 145 x 175
Powder Bed Fusion	**DMLS**	Metal	High	< 100um	High (>85Mpa)	Slow	500 x 280 x 360
	SLS	Polymer	Moderate	< 300um	Moderate (30~85Mpa)	Slow	750 x 550 x 550
Material Jetting	**NPJ**	Metal	High	< 50um	High (>85Mpa)	Slow	380 x 250 x 200
	MJ	Polymer	Moderate	< 25um	Moderate (30~85Mpa)	Slow	1000 x 800 x 500
Binder Jetting	**BJ**	Silica	Low	< 130um	Low (< 30Mpa)	Fast	4000 x 2000 x 1000
		Metal	High	< 130um	High (>85Mpa)	Fast	1800 x 1000 x 700
Direct Energy Deposition	**EBAM**	Metal	High	< 10um[4]	High (>85Mpa)	Fast	5790 x 1220 x 1220
Sheet Lamination	**LOM**	Polymer/Paper	Low	< 10um	Moderate (30~85Mpa)	Fast	256 x 169 x 150

2. Current 3D printing technologies

To understand the characteristics of 3D printing and advantages that it could bring to construction, it is essential to understand the different 3D printing technologies. ASTM, in collaboration with the International Organization for Standardization (ISO), published a document to define the standard terminology for 3D printing with seven different processes (ISO/ASTM52900-15, 2015) (Table 1):

-*Material extrusion*: a string of solid material is extruded through a heated nozzle on a build plate as a layer of the printing object following a predetermined path. Printing cost including material and the machine itself is at an affordable price range which makes FDM the most commonly used technology in consumer grade 3D printers. Though not suitable for replicating intricate shapes, FDM provides reliable quality to a certain level.

-*Vat photopolymerization*: this process selectively photopolymerizes polymer liquid (resin) using light. Stereolithography apparatus (SLA) and digital light processing (DLP) are types of 3D printing technology based on this process. While DLP uses digital projector to photopolymerize an entire layer at a time which makes DLP faster than SLA which uses beam of laser to scan desired surface thus takes longer time, screen resolution of DLP projector affects the quality of the result which usually is worse than that of SLA.

-*Power bed fusion*: selective laser sintering (SLS), direct metal laser sintering (DMLS) and etc. use layer of powdered materials and heat from laser to sinter layers together. Materials are bonded together in a molecular level in the process of melting and solidifying which makes printed object consistent and strong. Any material that melts under heat can be used, including metal, ceramic and etc.

-*Material jetting*: material jetting (Polyjet of Stratasys and MultiJet of 3D Systems), selectively jets liquid photopolymer materials like inkjet printers in layer by layer fashion. Considered as one of the most accurate 3D printing technology available, material jetting can create spectrum of colors or grades of softness by blending materials.

-*Binder jetting*: while both powder bed fusion (SLS, DMLS and etc.) and binder jetting use layer of powdered materials where power bed fusion uses heat from laser to sinter layers together, binder jetting uses adhesive materials as binding agents. Such characteristics make binder jet printed objects more brittle than those of SLS.

-*Direct energy deposition (DED)*: similar to material jetting process, DED also deposits materials in layers but uses intensive thermal energy to melt metal powder as it is being deposited. Typical applications include repairing and maintaining structural parts.

-*Sheet lamination*: laminated object manufacturing (LOM) used by Mcor (paper sheet) and Envisiontec (composite) are kinds of sheet lamination 3D printing technology. With trimmed sheet materials fused on top of each layers, LOM is considered as the fastest printing method available.

All of these processes have been implemented in many different industries for prototyping, production and proof of concept models (Sculpteo, 2018).

3. 3D printing in construction and architecture

Early experimental applications of 3D printing in the construction industry started appearing in the late 1990s. The first attempt that demonstrated the

1 https://www.additively.com/en/learn-about/3d-printing-technologies

2 https://www.sculpteo.com/en/glossary/3d-printing-speed-definition/ Speed may vary from cases.

3 Only well-known cases were presented. Sizes may vary from manufacturers.

4 After post CNC processing.

potential of construction 3D printing using cement based materials was suggested by Pegna (1997). He proposed freeform construction which involved selective deposition of Portland cement and rapid curing using steam. The work demonstrated that the principles of layered fabrication could be applied to construction process.

Since then, several large-scale construction 3D printing techniques have been explored for construction application. In 2004, Behrokh Khoshnevis at the Viterbi School of Engineering, University of Southern California, developed a gantry-based large-scale 3D printing system with trowels called Contour Crafting (Khoshnevis, 2004). In 2007, Enrico Dini developed another gantry-based powder jetting/bonding 3D printer, D-Shape, in which magnesium oxychloride cement, as a binding agent, is deposited to selectively harden a large-scale sand-bed (Dini, 2008). D-Shape can print up to 6 x 6 x 6m of architecture structures and has been used for a range of projects in construction. In 2007, Richard Buswell from Loughborough University developed a large-scale concrete printing process based on the extrusion of cement mortar (Buswell et al., 2007).

Integration of 3D printing technologies in construction industry to date is predominantly limited to cementitious materials based on extrusion process. Although concrete- and cement-based 3D printers are becoming a core method to fabricate buildings or construction components, daily practice with these techniques still seems far away due to the technological challenges such as insufficient material performance, implementation of reinforcement, insufficient qualities in surface finishes and rheology control of cementitious materials. For successful implementation of the extrusion-based 3DCP technology in the AEC field, high-quality final properties have to be targeted, further considering these issues in its practice.

3.1. Technical challenges in the extrusion-based 3DCP technology

Although there have been some improvements in developing and implementing large-scale 3D printers in the construction site since earlier attempts done by Yingchuang Building Technique Co. Ltd. (Winsun) and others, the extrusion-based 3DCP still confronts a number of challenges mainly caused by limited material performance of concrete. Concrete paste used in extrusion-based 3DCP, though is in its early stage of development and does have promising potential of improvement, does not yet have comparable consistency and viscoelastic property usually exhibited in polymer materials used in FDM printers which affects quality of printed object. This issue is normally arisen due to the fact that the material needs to go through a liquid stage and a hydration process to be solidified for successful self-supporting. For instance, Figure 1 shows defective tearing between deposited layers caused by cold joint and inconsistency in concrete paste commonly found in extrusion-based 3DCP building components. Such large thickness of concrete filament may serve its purpose of expediting printing speed, but perhaps limitations in material level as mentioned above are what really limit the thickness of concrete filament, hence affecting the dimensional resolution of extrusion-based 3DCP along with other mechanical factors.

Fig.1. Building wall built by extrusion-based 3DCP technology shows defective tearing of concrete filament caused by cold joints. (Winsun).

Low resolution of 3D printed parts is also what limits the application of extrusion-based 3DCP technology in the AEC field. Seen on Figure 2 and 3, jagged seams and surface texture caused by exceptionally low-resolution 3D printing process makes it hard to integrating them as building components along with other building components, if entire building is not being fully 3D printed. For instance, in Figure 2, seam detail between 3D printed part and other building part could not be effectively established thus mortar paste is used as a sealant to fill in the huge gap in between. Figure 3 shows similar issue in a structural level.

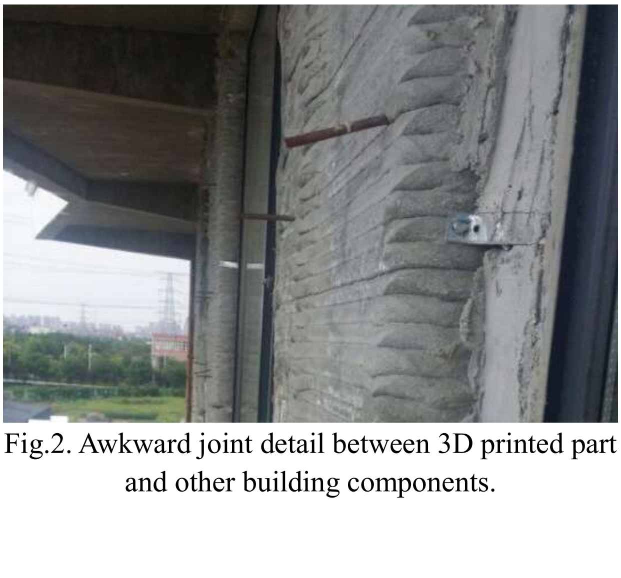

Fig.2. Awkward joint detail between 3D printed part and other building components.

Fig.3. Unestablished joint system between structural member and extrusion-based 3DCP parts.

Fig.4. electrical services not integrated into the printing process. Courtesy of Wu et al. (2016).

Figure 4 shows that electrical services were not integrated into the printing process, therefore requiring drilling which might cause potential problems to the structural integrity.

Those gaps in between 3DCP parts and other building components, including mechanical, electrical and plumbing, are not necessarily required to be filled out, but certain joint system is required to overcome compatibility issues caused by absence of clear joint system between parts made by extrusion-based 3DCP and other building components. A dedicated joint system utilizing other means of 3D printing technologies, either to be integrated during the printing process or as a post integration, could be devised as an alternative solution.

While Contour Crafting dominantly used 3D printing technology used in AEC field, best fit into FDM category in terms of base technology with unparalleled characteristics mainly demonstrated by its speed and build volume.

Having many aspect of adequate performance for construction scale 3D printing, Contour Crafting suffers from accuracy issue that dimensional tolerance exceeds well over 1,000 times the tolerance demonstrated by conventional 3D printing methods (Bos et al., 2016). Such method is only viable for limited use in building construction encompassed by wide spectrum of building components that vary in sizes and materials, vertical curved building shells, or smaller structures like emergency housing and pavilions.

4. Potential advantages of other 3D printing technologies in construction

There are a variety of other 3D printing technologies that have potential advantages to be applied at construction scale, as shown in Figure 5. A number of different approaches have been demonstrated to date which include on-site and off-

b) Smart Dynamic Casting process of slipforming, extruding concrete into a delimited formwork, controlled by a 6-axis robotic arm. Image: courtesy of Gramazio Kohler Research, ETH Zürich.

d) the AMIE demonstration structure printed by the Big Area Additive Manufacturing (BAAM) system. Image: courtesy of Oak Ridge National Laboratory, USA.

a) 3D printed formwork for a light weight ceiling of the Smart Slab project. Image: courtesy of ETH Zürich.

c) The MX3D's metal printer equipped with an industrial robot with an advanced welding machine, printing self-supporting steel bridge. Image: courtesy of MX3D.

e) stainless steel nodes, topologically optimized and 3D printed in metal by Arup. Image: courtesy of Arup.

Fig.5. Examples of other 3D printing technologies in construction.

site fabrication of buildings and construction components, including cladding, structural joints, panels and columns.

For instance, the DFAB House, an experimental building project developed by the interdisciplinary research conducted by eight ETH Zürich professorships as part of the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication and installed in the NEST building at Empa in Dübendorf, Switzerland, distinctively demonstrated the architectural and technical applications of the novel manufacturing and installation processes dealing with concrete constructions and structures (DFAB House, 2018). Smart Dynamic Casting (SDC) project explored the potential of slip-forming technology to create non-standard concrete structures based on either a free slipping trajectory or flexible actuated formworks (Lloret et al., 2015). SDC allows the bespoke fabrication of complex column structures in a continuous casting process integrated with internal deformed steel bars optimized by three-dimensional numerically controlled bending process (Asprone et al., 2018). In addition, the project Smart Slab, the 80m^2 lightweight concrete ceiling slab, achieves a level of complexity and precision out of concrete. Based on the particle-bed based 3D printed formwork, 11 prefabricated concrete elements together with a post-tensioning system and ultra-high performance fiber-reinforced concrete allow for the creation of highly optimized building components with complex structural configuration (Aghaei-Meibodi et al., 2017).

A Dutch startup known as MX3D focuses on the automated robotic additive manufacturing process of steel construction (MX3D, 2015). MX3D uses gas metal arc welding attached to two robotic arms to print an 8m stainless steel footbridge in Amsterdam. Through the addition of molten metal, this system makes it possible to create 3D objects that intersect in order to create self-supporting structures. In contrast to other material stacking printing techniques, which utilizes brick, plastics and concrete, this technique operates regardless of orientation and inclination without additional support structures, thus allows for the production of metal reinforcements for complex shaped concrete structures.

The research project demonstration, the Additive Manufacturing Integrated Energy (AMIE 1.0) (Biswas et al., 2017), led by a collaborative partnership of Skidmore, Owings & Merrill LLP (SOM), the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory (ORNL) and University of Tennessee, and Arup's 3D printed structural nodes for a large tensegrity structure installed in a shopping street in The Hague (Galjaard et al., 2015) show successful examples of exploiting other 3D printing technologies into AEC field. Rather than to fixating on traditional architectural materials, SOM chose to exploit the advantages of conventional FDM 3D printing technology along with polymer material commonly used by the very same 3D printing technology. AMIE 1.0 demonstrates features like complex, organic geometries that are optimized to reduce localized stress and mitigate turbulent exterior airflow that no traditional manufacturing methods can effectively replicate. Unprecedented use of direct metal laser sintering (DMLS) and direct metal tooling (DMT) technologies in AEC (mostly because of cost issue) shown on more recent case of Arup's 3D printed structural nodes overcomes cost and productivity issue by adopting automated FEM and topology optimization modeling process into freeform architectural components which can be cost effectively manufactured by DMLS or DMT 3D printing technology. In both SOM and Arup cases, they have managed to take advantage of the proven 3D printing technologies and materials into AEC which sharply contrast from current approach in concrete 3D printing.

Although many recent studies show promising future of concrete FDM printing, concrete FDM printing is still in its early phase of development and does not really shows clear advantages compared existing construction technologies at this stage. Furthermore, although flaws are being mitigated, common defects like imperfect layer adhesion and crude surface finish found on concrete FDM 3D printed buildings, shows certain limit of this technology.

As seen on Table.1, within the conventional field of 3D printing technology, though fewer may survive in the future, each technology has its pros and cons that serves for its suitable purpose. To abridge lagged adaptation of concrete FDM 3D printing in AEC field caused by shortcomings of concrete FDM technology, other 3D printing technologies should be taken into consideration in conjunction with concrete FDM technology.

5. Conclusion

This paper provides an overview of the challenges of the current concrete extrusion 3D printing technique, and considers the possibilities of other 3D printing technologies for the production of building-scale construction. Construction 3D printing can bring significant changes to the construction industry enabling mass customization using prefabricated products, and open up a frontier to use new materials.

Despite superior building volume and speed along with other key advantages of extrusion-based 3DCP technology against other 3D printing technologies, innate issues persist. Seen in Table 1, there is no one perfect universal solution that fulfills every expected engineering requirements, which also is a common case for other technologies out there as well. As demonstrated in many cases, 3D printing technologies including extrusion-based 3DCP shows both their own potentials and limitations.

While no 3D printing technology has proven to be more effective in every aspect against others, implementation of 3D printing technology in AEC field has been very selective despite the spectrum of available 3D printing technologies.

Along with previous architectural 3D printing projects by ARUP and SOM, recent architectural 3D printing studies like Smart Slab Project by ETH Zürich have started to show successful implementation of integrating multiple 3D printing technologies with promising results.

In same perspective, though extrusion-based 3DCP is unique amongst other available 3D printing technologies that this technology allows unparalleled printing speed and build volume and material level compatibility with other building components that no other 3D printing technology can provide, yet issues like reinforcement, MEP integration and dimensional accuracy remain persistent with no clear solution. Alternative approaches in association with other 3D technologies would yield effective solutions to current issues regarding extrusion-based 3DCP which may expedite wide adaptation of advanced 3DCP technologies in AEC field.

6. Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2017R1D1A1B03035650).

7. References

1) Aghaei-Meibodi, M., Bernhard, M., Dillenburger, B. & Jipa, A. (2017) The smart takes from the strong. Fabricate 2017: Rethinking design and construction. London, UK: UCL Press.
2) Asprone, D., Menna, C., Bos, F. P., Salet, T. A. M., Mata-Falcón, J. & Kaufmann, W. (2018) Rethinking reinforcement for digital fabrication with concrete. Cement and Concrete Research, 1-11.
3) Biswas, K., Rose, J., Eikevik, L., Guerguis, M., Enquist, P., Lee, B., Love, L., Green, J. & Jackson, R. (2017) Additive manufacturing integrated energy—Enabling innovative solutions for buildings of the future. Journal of Solar Energy Engineering, 139, 015001-10.
4) Bos, F., Wolfs, R., Ahmed, Z. & Salet, T. (2016) Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping, 11, 209-225.
5) Buswell, R., Gibb, A., Soar, R., Austin, S. & Thorpe, T. (2007) Applying future industralised processes to construction. Proceedings of CIB World Building Congress, Cape Town, South Africa.
6) DFAB House. (2018), viewed 13 Aug 2018, <http://dfabhouse.ch/dfab-house/>.
7) Dini, E. (2008) D-Shape, viewed 7 Aug 2018, <http://www.d-shape.com>.
8) Galjaard, S., Hofman, S., Perry, N. & Ren, S. (2015) Optimizing structural building elements in metal by using additive manufacturing. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015, May 13 Amsterdam, The Netherlands. 1-12.
9) Gibson, I., Kvan, T. & Ming, L. W. (2002) Rapid prototyping for architectural models. Rapid Prototyping Journal, 8, 91-95.
10) ISO/ASTM52900-15 (2015) Standard Terminology for Additive Manufacturing – General Principles – Terminology, West Conshohocken, PA, American Society for Testing and Materials.
11) Khoshnevis, B. (2004) Automated construction by contour crafting-related robotics and information technologies. Automation in Construction, 13, 5-19.
12) Lim, S., Le, T., Webster, J., Buswell, R., Austin, S., Gibb, A. & Thorpe, T. (2009) Fabricating construction components using layer manufacturing technology. Proceedings of the Global Innovation in Construction Conference 2009(GICC'09), Loughborough, UK.
13) Lloret, E., Shahab, A. R., Linus, M., Flatt, R. J., Gramazio, F., Kohler, M. & Langenberg, S. (2015) Complex concrete structures: Merging existing casting techniques with digital fabrication. Computer-Aided Design, 60, 40-49.
14) McCue, T. J. (2018) Wohlers Report 2018: 3D printer industry tops $7 billion: Forbes, viewed 2 Aug 2018, <https://www.forbes.com/sites/tjmccue/2018/06/04/wohlers-report-2018-3d-printer-industry-rises-21-percent-to-over-7-billion/#1e996cff2d1a>.
15) MX3D. (2015) MX3D Bridge, viewed 21 Aug 2018, <http://mx3d.com/projects/bridge-2/>.
16) Pegna, J. (1997) Exploratory investigation of solid freeform construction. Automation in Construction, 5, 427-437.
17) Sculpteo (2018) The state of 3D printing: The data you need to understand the 3D printing world and build your 3D printing strategy, Paris, France.
18) Wu, P., Wang, J. & Wang, X. (2016) A critical review of the use of 3-D printing in the construction industry. Automation in Construction, 68, 21-31.