APPLICATIONS OF ADDITIVE MANUFACTURING IN CONSTRUCTION INDUSTRY: A LITERATURE REVIEW

Abdelhakim A. Al Turk1
Gamal S. Weheba1
1Department of Industrial, Systems and Manufacturing Engineering, Wichita State University
gamal.weheba@wichita.edu

Abstract

Additive manufacturing is the process where three-dimensional parts are constructed layer-by-layer based on their computer-aided design (CAD) models. AM has gained a strong reputation in the aerospace and medical industries, and its use is now considered revolutionary. In the past few years, the utilization of AM technology has been expanded and is now leading to breakthroughs in the construction industry. This paper provides a state-of-the-art review of the use, advantages, and limitations of AM in the construction industry. The review sheds light on the different AM techniques used and highlights contemporary projects and achievements in the construction industry.

1. Introduction

Additive manufacturing (AM) has been defined by the American Society for Testing and Materials (ASTM) as “the process of joining materials to make objects from 3D model data, usually layer upon layer.” Even though materials and ways vary, the basic process divides the CAD model into layers and constructs them as prototypes or end-use products. Originally, the technology was confined to creating prototypes to support new product design activities. Currently, all AM techniques have been successfully adopted for the manufacturing of functional end-use products. Among these techniques are Stereolithography, Binder Jetting, Material Jetting, Powder Bed Fusion, Material Extrusion, Sheet Lamination, and Directed Energy Deposition. These techniques can create solid objects in layers by using different materials and methods for bonding them together. A more detailed description of these techniques can be found in the ASTM F2792 Standards.

In the construction industry, the constant growth of AM led to a wide range of applications. Design modeling, automated construction of full structures or structural elements, restoration of historical buildings, and repair of existing structures are examples of current applications of AM in this industry. Early adoptions of the AM technology appeared to target restoration projects. Rather than focusing on solid 3D-printed parts, some construction firms utilized the technology to construct concrete molds. These plastic molds were inlaid with wire mesh to reinforce the cast. A good example of this application is the process developed by Edg (edgnyc.com), an architecture and engineering firm in NY. This paper is focused on large-scale AM systems that have been developed and utilized in construction projects. The following sections present a review of Contour Crafting, Binder Jetting, and Hybrid Systems currently utilized in the industry.
2. **Contour Crafting**

Contour Crafting (CC) is a layered fabrication technology introduced by Khoshnevis in 1986. In his article, Khoshnevis (2003) described CC as a process that uses a computer to exploit the superior surface-forming capability of a bladed trowel for creating smooth and accurate surfaces with intricate features. A distinguishing feature of CC is its capability to fabricate large-scale objects. The process is based on combining an extrusion system with the filling process to build concrete objects as shown in Figure 1. As the material is extruded through an extrusion nozzle, the top and side trowels work on the material to create a smooth outer edge of the rim. The filling process consists of pouring material to fill the area constructed by the extrusion nozzle.

![Figure 1. Schematic of the Contour Crafting Process](image)

CC is a layered manufacturing technique that offers a potential solution for difficulties faced in the construction industry. Higher fabrication speed, improved surface quality along safety benefits are some of the advantages offered with this technology as was noted by Khoshnevis et al. (2006). The use of two trowels greatly influences the surface finish and quality of the final objects. Typically, top and side trowels are perpendicular to each other. The latter is capable of pivoting to facilitate the creation of the rim surfaces with non-orthogonal shapes. Trowel geometry, height, and rotation are key factors in achieving accurate and smooth surfaces. The pouring mechanism is still needed to fill the area bounded by the rim walls.

In 2014 WinSun, a Chinese Engineering Design Company achieved success in building concrete houses shown in Figure 2 using CC technology. During this project, 10 concrete houses were built in Shanghai, China, within one day. The area of each house was 195 m$^2$ at the cost of $4800. The construction was performed using four giant printers. Each printer is about 10 meters wide and 6.7 meters high. The basic components of each house were built offsite and then assembled on site.
In 2015, the same company constructed the tallest 3D printed structure. This project consisted of constructing a five-story apartment building. The total area of this project was about 1100 m², making it the tallest 3D printed structure in China to date. According to WinSun, using this technology reduced the construction time by 50%-70%, labor cost by 50%-80%, and material costs by 30%-60%. By the end of 2015, WinSun achieved another milestone by constructing the world’s first 3D printed villa. The total area of this villa is approximately 1,100 m² complete with internal and external decoration. WinSun holds 98 national patents for construction materials.

In 2016 Huashang Tengda, another Chinese company, constructed a two-story villa, using similar printing technology in 45 days. The total area of this project was 400 m². The project started after all the plumbing pipes and steel reinforcements were installed. The project utilized a standard class C30 concrete containing coarse aggregates. According to the Huashang company, the building is safe and can withstand earthquakes of magnitude 8.0 on the Richter scale.

In 2016, some researchers from the University of Federico II, Italy, configured the WASP 3D printer, capable of printing 3 m long concrete beams using CC printing technology. Using this system, a 3 m tall cave, called the Y-Box Pavilion was structured in Thailand. The construction cost was around $28,000. The components of this project were constructed offsite and then assembled on site.

Figure 2. Concrete Houses by WinSun

Figure 3. Apis Core World’s biggest 3D printed building
In 2019, Apis Core, a US-based Company, completed the World’s Largest 3D printed building shown in Figure 3. This company printed wall structures of a two-story building for the Dubai Municipality. The walls are 9.5 meters tall and the area of this project is 640 m². This project entered the Guinness Book of World Records as the World’s largest 3D printed structure to date. Also, all the project was constructed on-site without any off-site assembly work. According to Apis Core, this project was completed under critical environmental conditions, since the work area was not covered.

3. Binder Jetting Technology

As reported by Gibson et al (2015), this technology was developed at MIT in the early 1990s. Originally, it was called 3D Printing (3DP) in which binder material is printed onto a powder bed to form one layer of the object. Once the first layer is constructed, a fresh layer of powder is spread over the bed, smoothed by a roller, and the binder is applied. These steps are repeated until the object is constructed. A schematic presentation of the process is shown in Figure 4.

![Figure 4. Schematic of the Binder Jetting Process](image)

Depending on the material and the binder used, heat may be applied to assure adhesion within and between layers. The extra powder has to be removed using vacuum or compressed air during post-processing steps. Typically, constructed objects require some infiltration to increase their mechanical properties.

Early applications of the binder jetting process in construction were reported by Duxson et al (2006), by utilizing a geopolymer instead of the standard ceramic powder material. This is a mix of slag and fly ash, a type of alkali aluminosilicate, with the same characteristics as cement. They used a Z-Corp 450 3DP system with the standard Zb 63 binder. Under these conditions, the geopolymer material was shown to have some advantages over the standard cement including good resistance to sulfate and acid attack, high compressive strength, and low shrinkage. They proposed a new post-processing technique and tested five different mixes of geopolymers. They recommended using a mix of 100% slag and 0% fly ash and concluded that the new post-processing technique significantly increased the strength of the constructed samples.

In 2007, Monolite Ltd, a British company, introduced its d-shape process. This is a 3DP-based process capable of printing architectural components using micro-concrete powder with an inorganic binder in layers of 5-10 mm thickness. The powder is made of granules of different materials ranging from 0.2 mm to 5 mm size.
The process is claimed to construct components with marble-like properties. The company offers four different configurations with build volumes of up to 12 m x 12 m x 10 m. Printers are equipped with mixers and feeding systems to deliver the material to the powder spreader. A vacuum system is used to remove unbounded powder during post-processing stages. The constructed components are typically ground and polished to the final shape. The process was successfully utilized in constructing a 1.6 m high architectural pieces called “Radiolaria” depicted in Figure 5.

Recently, Xia et al (2019) reported on applications of 3DP technology for concrete printing using geopolymers. They considered the effect of different powder parameters and binder droplet penetration behavior on the printability of the geopolymers. They also investigated the effect of fly ash content on the compressive strength of the printed specimens. The results indicated that geopolymers can be used in the commercially available binder jetting systems.

![Figure 5. The Radiolaria: Example of full-scale build using the d-shape process](image)

4. Hybrid Systems

Hybrid systems combine the flexibility of additive systems and the accuracy of traditional subtractive processes. The additive component of these systems covers the concept of building parts layer by layer. Whereas, the subtractive component covers computer numerical control (CNC) machining operations including drilling, milling, and grinding. This combination allows the construction of tools and models used for concrete casting. The definition of hybrid systems in the ASTM F2792 Standards is restricted to laser metal deposition combined with CNC machining. However, Zhu et al (2013) described a hybrid system as a “combination of an additive and subtractive processes, sequential or integrated, including planning for fixturing and orientation in the quest of a final, usable part.” Under this wider definition, hybrid AM systems would include a much larger number of AM systems. Examples include Sheet Lamination (e.g., Ultrasonic AM) and some Material Jetting systems like 3D Plotters.

Thermwood, a US-based company, is a leader in large scale additive manufacturing of thermoplastic composite molds, tooling, patterns, and parts. Its line of Large Scale Additive Manufacturing (LSAM, pronounced L-Sam) machines uses a two-step process. The part is 3D printed layer by layer, to slightly larger than the final size, then it is trimmed to its exact final net size and shape using a CNC router. Thermwood’s LSAM Print3D software utility, which operates within Mastercam, is used to generate the CNC print program needed to print the part using the print gantry. The CAD model is then used to generate a trim program that is used to finish the part using the trim gantry.
Although suitable for producing a wide variety of components, Thermwood is focusing on producing industrial tooling, masters, patterns, molds, and production fixtures for a variety of industries. In 2017 Thermwood demonstrated its ability to print and trim a concrete mold out of carbon fiber-filled ABS. The company offers three models of the LSAM with the same working principle but different sizes. The build size of the 1040 model (shown in Figure 6) is 3.0 m x 12.2 m, with a maximum height of 1.5 m. Their standard 40 mm melt core (extruder) has a maximum output of between 86.2 kg and 95.3 kg per hour, depending on the polymer used.

5. Cited Advantages

As reported by Camacho et al (2018), an essential advantage of 3D printing is its ability to produce complex geometries that were hard or even impossible to construct with conventional construction methods. Large-scale 3D printing of end-use structures allows architects to build complex passageways, undercuts, and other interior and exterior designs. They are allowed to rethink their sketches and forms without affecting the productivity of the construction process. Architects do not have to worry about the constructability of each part anymore and can now focus on their design and functionality. The Radiolaria project, in Figure 5, is a perfect illustration of geometric freedom made possible by AM.

In traditional construction, the use of formworks is a must. Formworks are made of pieces of wood assembled to give the finished concrete its desired shape. Camacho et al (2018), pointed out that 3D printing allows for the reduction or elimination of formworks. They also noted the potential benefits of using the technology for in-situ repairs of existing structures. They indicated that AM could be used to construct temporary support structures inside the damaged building to allow for inspection and even restoration, thus decreasing the risk of work-related injuries.

Noguchi et al (2018) indicated that applications of AM in the construction industry will lead to cost reduction. 3D printing of concrete structures was reported to reduce the project cost by decreasing the amount of labor, material, formworks, and the project lead-time.

More importantly, as was noted by Khoshnevis (2003), the construction industry is a significant source of waste around the world. Conventional construction activities often consume a sizable amount of natural resources like water, wood, sand, and fine and coarse aggregates while polluting the environment with hazardous emissions and byproducts. He estimated that seven tons of waste is generated each time a conventional house is built using traditional construction methods. AM will help minimize this waste and replace traditional construction methods by the environmentally friendly, emission-free, electrical 3D printing systems.
6. Cited Challenges

As in all potential applications of AM, a major challenge facing concrete printing is the availability of materials. Le et al. (2012), indicated that the concrete used for 3D printing needs to have special characteristics concerning its hardening, compressive strength, flowability, and stability. Concrete must bond together to form each layer; it must have enough buildability features to enable it to lay down properly and remain in position. For extrusion-based processes, the concrete must be stiff enough to support further layers without failing with an adequate degree of extrudability. Also, there are conflicting requirements between the flowability of the mix, setting speed, workability, buildability, and the resulting compressive strength. These represent challenges for the widespread applications within the industry.

As was noted by Tay et al. (2017) projects constructed using CC and similar systems contain no steel reinforcement, and hence have low tensile strength. These structures must be designed with hollow voids to add the steel later. This may limit the freedom of architectural design. They also indicated that the need for highly skilled labor, capable of operating printers and integrating robotics, is another challenge for AM in construction. They anticipated that re-training of current labor and incorporating newer trainees will become mandatory as 3D printing use expands over the next few years.

Also, as stated by Abderrahim et al. (2003), the first challenge faced in the construction industry is workers' safety. Studies have indicated that primary hazard sources are collisions with machines. Zhou et al. (2013) pointed to the need for eliminating human activities during the 3D printing process to minimize the risk of injury. They proposed installing a real-time camera to monitor and recorder activities around the printer to improve safety and reduce accidents.

7. Conclusion

Successful applications of AM in Aerospace, Automotive, and the Medical industries have drawn the attention of other industries including the construction industry. The availability of large-scale systems is encouraging architects and designers to try their innovative ideas away from the restrictions of traditional construction methods. Applications are beginning to reveal the benefits of AM throughout the life cycle of construction projects. It appears that the development of large-scale systems has been focused on concrete printing. Both on-site and off-site systems are now commercially available. On-site printing systems offer great flexibility in design with the elimination of the need for labor-intensive, costly formworks. However, the process and materials used appear more sensitive to environmental conditions. Off-site systems, on the other hand, offer these similar benefits but operate under controlled conditions. This provides a better opportunity for assuring construction quality and speed. A disadvantage, however, is the need to transport the printed components to the construction site at a significant cost.

While concrete printing has potential in several areas, there is a need for continuing research in areas of materials, mechanical properties of final components, and process control. Processes need to be reexamined to allow for reinforcement of concrete. Mechanisms for integrating different reinforcement materials, patterns, and shapes during component printing need to be considered. Other AM techniques like sheet lamination, which is capable of integrating sensors and electronic monitoring devices may prove useful in construction projects. The need for skilled labor is a challenge facing the adoption of AM in all industries including construction. As public interest in the AM technology increases, more education and training programs are being offered. The more designers and engineers are trained on the technology, the better the chances are for efficient and effective implementation.
8. References


Apis Core, Online: https://www.apis-cor.com, (accessed 30.01.20).


