Applications of Additive Manufacturing in the Construction Industry – A Prospective Review

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Abstract –

Additive manufacturing (AM), also known as 3D printing, produces components by building-up structures from small deposits of materials. Many of the early applications of AM technologies have been in the aerospace, automotive, and healthcare industries. Building on the advances in AM in these industries, there are several experimental applications of AM in the construction sector. Early investigations suggest that use of AM technologies for construction have the potential to decrease labour costs, reduce material waste, and create customized complex geometries that are difficult to achieve using conventional construction techniques. However, these initial investigations do not cover the full range of potential applications for construction or exploit the rapidly maturing AM technologies for a variety of material types. This paper provides an up-to-date review of AM as it relates to the construction industry, identifies the trend of AM processes and materials being used, discusses related methods of implementing AM, and potential advancements in applications of AM. Examples of potential advancements in methods and applications include multi-material use (e.g., use of high-performance materials only in areas where they are needed), in-situ repair in locations that are difficult or dangerous for humans to access, disaster relief construction in areas with limited construction workforce and material resources, structural and non-structural elements with optimized topologies, and customized parts of high value. AM's future in the construction industry is promising, but interdisciplinary research is still needed to provide new materials, new processes, faster printing, quality assurance, and data on mechanical properties before AM can realize its full potential in infrastructure construction.

Keywords –

Additive Manufacturing; Construction Industry, 3D Printing

1 Introduction

Additive Manufacturing (AM), commonly known as 3D printing, produces components by building-up structures from small deposits of materials. AM is a rapidly growing field, having an impact in multiple industries, revolutionizing design, and simplifying the processes to go from a 3D model to a finished product. Comparing AM with other manufacturing processes such as formative processes, where material is deposited in a mould that has the desired shape, and subtractive processes, where a solid piece of material is cut into the desired shape, formative processes require the production of the mould to manufacture a product in mass quantities, and subtractive processes produce waste material, as the material being cut is not reused. AM can advantageously create a wide range of shapes without the need of a mould and only using the required material, filling a gap left by the other manufacturing processes.

Aerospace, automotive, healthcare, and architecture industries have explored the benefits of using AM in their businesses. First uses were for rapid prototyping, to reduce time when producing prototypes with complex geometries [1]. Since then, AM has evolved to include other applications beyond rapid prototyping, and other industries such as construction are starting to follow the early adopters of these new AM technologies.

There have been several experimental applications using AM in the construction industry starting in the late 1990's [2]. This paper provides an up-to-date review of experimental AM technologies in construction, identifies the trend of AM processes and materials being used, discusses related methods of implementing AM and potential applications, and identifies research needs to foster more widespread use of AM in construction. It serves as a guiding point for researchers interested in the area, to understand what has been done so far and what can be done.

2 Current Construction Industry and Potential for AM Technologies

As in every industry, there are challenges being faced. For construction, those challenges have been identified decades ago, such as work in harsh environments, a decrease in productivity, decrease of a skilled workforce, safety during construction, producing large amounts of waste material, and transportation of materials to the site to mention some [3,4].

Construction is considered a high risk profession, having the largest number of deaths in any sector [5]. When construction in harsh environments is unavoidable, the difficulty and risks increase, affecting construction quality and/or adversely human safety. AM could provide services to the construction industry by reducing exposure of on-site workers to harsh environments and by automating some of the construction tasks.

AM allows customized parts to be printed on-demand from a 3D model without significant lead time. Instead of having multiple companies or trades producing different structural or non-structural components, each component can be produced directly using AM after it is designed, tackling one of the challenges previously mentioned, decrease in productivity.

Besides decreasing productivity, there is also a decrease of a skilled workforce. Contractors are having a hard time finding a workforce with the required skills, requiring more time and money to train them. The use of AM in construction will require different skill sets than in current practice, shifting from a labour-intensive work environment to a more technical environment, requiring computer and manufacturing skills.

Another potential benefit from AM, is the reduction of formwork used during construction. Currently, concrete structures are commonly built using temporary formwork to maintain the desired shape of wet concrete as it hardens, and that formwork labour and material ranges from 35-60% of the overall cost of the concrete structures [6]. Reducing formwork use, not only reduces waste material produced during construction, which is considered to be about 23% of the total material wasted in the country [2], but it also reduces construction cost and time that is required for placing and disassembling the formworks.

A common practice in the construction industry is off-site fabrication, as it reduces exposure to on-site working hazards (e.g., harsh environments, safety accidents, etc.) and increases construction quality and consistency; however, such precast elements, modules, and structural assemblies must be transported to the job site. If on-site AM could be implemented, the number of structural and non-structural parts or assemblies that must be transported to the site can be reduced.

3 Additive Manufacturing Processes

AM is achieved in many different ways and the American Society for Testing and Materials (ASTM) International, published a document in collaboration with the International Organization for Standardization (ISO) to define standard terminology for AM [1]. In this document, ISO/ASTM divided AM into seven different processes explained below:

- **Vat Photopolymerization (VP)** – A process of selectively curing a liquid light-activated polymer with a laser. An example of this process is stereolithography apparatus (SLA), a technique developed by Charles Hull in the 1980's [7] and commercialized by 3D Systems.
- **Material Jetting (MJ)** – A process of selectively depositing drops of material in a layerwise fashion. 3D Systems, Inc. uses this process to print customized dental prosthetic devices such as crowns and copings with high precision using UV curable plastic [8].
- **Binder Jetting (BJ) –** A process of depositing a powdered material layer upon layer and selectively dropping a liquid binding agent onto each layer to bind the powders together. Binder jetting was primarily developed at MIT in a process called 3D printing (3DP) [7].
- **Material Extrusion (ME) –** A process of extruding material through a nozzle and depositing it layer-by-layer onto a substrate. The process was invented by Scott Crump and commercialized by Stratasys as Fused Deposition Modelling (FDM) [7], but it now forms the basis for a very wide variety of inexpensive personal 3D printers.
- **Powder Bed Fusion (PBF) –** A process of selectively fusing a powder bed using thermal energy, typically in the form of a laser or electron beam. Selective Laser Sintering (SLS) was developed at the University of Texas at Austin for polymer materials and commercialized by DTM and 3D Systems [7].
- **Sheet Lamination (SL)** – A process of successively shaping and bonding sheets of material to form an object. An example of sheet lamination process is laminated object manufacturing (LOM) developed by Helisys Inc., in which paper sheets were trimmed to size and glued together [7]. Ultrasonic Additive Manufacturing (UAM), commercialized by Solidica Inc. fabricates metal objects using ultrasonic welding [7].
- **Direct Energy Deposition (DED) –** A process of fusing materials with focused thermal energy that melts the material as it is being deposited. An example of this process is laser engineered net shaping (LENS), developed at Sandia National

Laboratories [7], which is particularly useful for repair of damaged metal parts [9]

4 AM in Construction

Table 1 presents examples of AM technologies used for construction and/or companies using these technologies, categorized by materials, AM processes, and spatial delivery system. It can be determined from Table 1 that most of the work being done so far has been in aggregate based material extrusion. As evidenced by their absence in Table 1, work in the area of vat photopolymerization, material jetting, and sheet lamination has yet to be explored in the construction industry to the extent of the authors' knowledge.

Most of the technologies deliver material using a gantry system, but some of them have explored the use of a robotic arms. Although gantry systems have been most commonly used, they do have limitations as discussed by others [5,10,11], such as transportation, installation, orthogonal deposition, and size of the system. Some AM technologies use robotic arms because of the increased freedom provided with its six-axis motion and flexibility to program multiple tasks for the robotic arm. Additional information on key AM technologies and applications are provided in the following sections as categorized by material.

4.1 Aggregate Based

The first ideas of producing elements for construction using AM were proposed in the late 1990's [2]. One of the first to recognize its potential was the University of Southern California (USC), where Contour Crafting (CC) was developed [13]. CC utilizes a gantry system to extrude thick layers of cementitious material in order to increase deposition rate for large-scale structures. The technology has trowels attached on the side of the nozzle to smooth the horizontal and vertical surfaces of the material being extruded [32].

WinSun is a Chinese company that worked jointly with architectural and structural design companies such as Gensler, Thornton Tomasetti, and others to build an office building for the Dubai Future Foundation (Fig. 1), which was printed in Shanghai, shipped to Dubai, and then assembled on site. The cost of printing and assembling was around $140,000 for the 242 m^2 (2,600 ft^2) single-story building, and compared to conventional construction techniques construction waste was reduced by 30 to 60% [33,34].

Figure 1. Dubai Future Foundation Printed Office Building [33]

4.2 Polymers

Although the use of polymers in construction is not as common as aggregate based and metals, polymers could be used in construction for aesthetic purposes or in structural applications when combined with other strength-enhancing materials.

Table 1. Example of AM technologies in the construction industry

AM Process	Aggregate Based			Polymer		Metallic	
	Gantry	Robotic	Other	Gantry	Robotic	Gantry	Robotic
BJ	Pegna [2] D-Shape [12]						
ME	Contour Crafting [13] Concrete Printing [14] WinSun [15] TotalKustom [16] BetAbram [17] 3D Concrete Printing (3DCP) [18]	XtreeE [11] CyBe [19] Apis-cor [20]	WASP [21] MiniBuilders [22]	BAAM [23] Qingdao Unique Products Develop [15] KamerMaker [24]	C-Fab [25] Digital Construction Platform (DCP)[26] FreeFAB™ Wax [27]		
PBF				Skanska* [28]		Arup*[29] Permasteel-isa*[30]	
DED							MX3D [31]

*Company using a technology

Skanska is a construction company that has utilized advancements in the area of AM by printing unique cladding for the Bevis Marks Building in London. The complex geometry of these connection regions made AM an attractive option for the architectural cladding that had decorative purposes only (shown in Fig. 2) [28]. This application by Skanska proves that AM can be used to provide unique architectural designs without requiring complex and costly production processes.

Figure 2. Bevis Marks Roof (Cladding) [28]

4.3 Metallic

Table 1 shows that metallic material is the group least being explored. The small-scale components built using AM exhibit comparable strength properties to conventionally manufactured components, but they are cost prohibitive using current AM technologies [29]. The advantages of AM become more evident when building up structures or components with complex geometries designed to optimize weight and material use that would be difficult, if not infeasible, to manufacture using conventional techniques.

An example of using AM for optimized structural topologies was developed by Arup. Arup designed several variations of a node using conventional and AM techniques (Fig. 3) to demonstrate the potential savings that can be attained through topology optimization and AM. Although the structure was already built at the time of the investigation, Arup estimated that topology optimization and AM could reduce the weight of each node by 75% compared to the original design, resulting in an estimated reduction of more than 40% for the weight of the entire structure [29].

Figure 3. Arup’s Optimized Node [29]

5 Potential Advancements in Methods of Implementing AM

Work done so far in AM has identified different opportunities in which use of AM could be advantageous to conventional techniques such as building up components using multiple materials, using in situ resources, utilizing hybrid techniques that combine AM processes with subtractive and/or formative processes, and expanding opportunities for both off-site and on-site fabrication. These advantageous methods of implementing AM in construction are discussed below.

5.1 Multiple materials

AM could allow multiple materials to be deposited during the construction using extrusion based processes with multiple nozzles for different materials. Bos et al. [18] proposed a concept of material customization by location. For example, depositing ultra-high performance concrete where structural demands are largest, and low-strength concretes for finishes and areas where structural demands are lower. The potential of printing multiple materials, is something that could bring advantages in the construction industry, but research is needed to develop new construction materials that are optimized for use in AM while still providing desirable structural performance. At the same time, these new materials must be economical for AM to become a feasible alternative in construction [35].

5.2 In situ resources

Being able to build using locally available resources can reduce material transportation costs and can provide more sustainable design solutions for places that are difficult to access. CC and D-Shape are investigating the possibility to use their technology to build structures using in situ resources such as regolith rock on the Moon, since sending raw construction material to the Moon is very difficult and expensive [36]. Another technology known as WASP (World’s Advanced Saving Project) has focused on using AM technologies to build “zero-mile homes” that utilize on-site materials to creating housing in places where it is hard to find access to construction materials [21]. Research using in situ resources is still in its early stages, only proving the concept of building up layers of materials collected from surrounding areas, but further research is needed to decrease printing time, assure the desired material properties, develop customizable designs, and ensure repeatability.

5.3 Hybrid techniques

Hybrid systems that combine subtractive, formative, and additive processes could be implemented to facilitate the incorporation of AM in construction. Taking advantage of the benefits of each technique, while still exploring new materials, processes, and technologies provided by AM, will foster an environment for innovation in construction. An example is MIT’s DCP which is a hybrid system with the intent of designing, sensing, and fabricating a component on site, trying to incorporate additive, subtractive, and assembling techniques in one all-purpose construction system [26]. MIT’s DCP combines rapid foam extrusion to serve as formwork and insulation and milling techniques to provide desired finish rapidly [26]. Hybrid techniques can provide the first steps for introducing AM into the construction industry while further work is done to address challenges that limit the widespread use of AM in construction.

5.4 Off-site/On-site Fabrication

The use of AM has been geared mainly for off-site fabrication where a gantry or robotic arm system in a controlled environment is used for both small and large scale applications. The controlled environment is desirable as materials used can react differently and provide different mechanical properties if the environment is suddenly disturbed. The current on-site fabrication AM systems still require certain environmental conditions be met for best results. Alternatively, research can be done to develop materials for AM that are not sensitive to environmental factors for improved mechanical properties. Currently, off-site fabrication is the most reliable way to produce components using AM; however, technologies and materials suitable for on-site fabrication can be further developed to provide the most benefits in construction, reducing transportation of components to the site and at the same time providing capabilities to provide repairs and last minute design changes for structures in various stages of completion.

6 Potential Advancements in Applications of AM

AM is starting to gain recognition in the construction industry based on the success it has so far in the other industries. Several proof-of-concept experimental applications have already been implemented in construction, but furthermore research is needed to fully develop and improve the technology. Some potential applications ideal for AM technologies have been identified and are explained more in detailed below. The challenges and gaps that must be filled to fully develop and implement the technology in the construction sector are also discussed. Table 2 summarizes these potential applications, relates them to some of the existing experimental technologies, and comments on development needs.

Table 2. Potential advancements in applications of AM in the construction industry

Potential Applications	Examples of AM Technologies		Future Development Needs
Topology Optimization	D-Shape Contour Crafting Concrete Printing 3DCP* XtreeE	BAAM KamerMaker Skanska Arup Permasteelisa MX3D	Standards and testing/Quality control Precision Large scale testing Structural applications Bonding New design approach
Customized Parts	Skanska		Large scale additive manufacturing Structural applications Faster printing On-site printing
In situ repair			Identify areas that need repair Automation On-site printing Bonding
Novel Forms	D-Shape Contour Crafting Concrete Printing 3DCP* XtreeE CyBe* Apis-cor	BAAM KamerMaker C-Fab Skanska Arup MX3D DCP* FreeFAB^{TM} Wax	Large scale additive manufacturing Structural applications Faster printing On-site printing
Tolerance Matching/Correcting			Identify areas that need repair Automation
* Currently Under Development			

6.1 Topology optimization

AM's capability of producing components layer by layer can be used to produce structural elements with optimized topologies, where material is only deposited where it is most needed to resist structural demands. This advantage minimizes the use of material and reduces structural weight. XtreeE has investigated optimizing an element where the voids where material is not needed for structural purposes could provide additional functionality, such as thermal insulation and sound proofing [11,14].

Although these concepts of topology optimization have been explored by many, several challenges come into play when reducing the amount of material required for an assumed loading scenario, such as producing structures and components with reliable material properties and sufficient levels of safety. To provide the levels of safety expected by modern engineering standards, more detailed information on material properties, uncertainty, and quality assurance protocols is needed.

6.2 In situ repair

The potential benefits of using AM for in situ repair of existing structures are evident. As they age, buildings often require maintenance, rehabilitation, and/or replacement. Maintenance or in-situ repairs could be done using machines that could scan the structure, detect the areas needing a repair, and do the repairs using AM techniques or even using hybrid systems. Another potential application is to repair infrastructure that is damaged by a natural or man-made disasters. AM could be used to construct a temporary support structure inside this damaged building to allow for inspection and even restoration.

Future work is still needed to improve the automation process of placing material on an existing structure first before moving to more complicated and multi-step tasks of detecting current conditions of a structure, using subtractive processes to remove damaged areas, and then repairing what is needed. Referencing Table 2, it can be seen that no research has been done that includes both the use of AM and automation of tasks for repairs in construction. Most of the existing AM technologies for large-scale applications are not suitable for changing working area conditions that may be encountered during repair situations.

6.3 Customized parts

Although construction cost can be reduced by reducing labour, material, transportation, and time required for a project, past studies have indicated use of AM in construction may significantly increase costs. Mrazovic [30] states 3D printing steel components using powder bed fusion is possible but will likely be cost prohibitive, mainly due to the processing speed. Conversely, WinSun claims that labour costs for the Dubai Future Foundation building was reduced by 50 to 80% using AM [33]. Once the materials and machines become more common in the market, the cost associated with using AM will be reduced through economy of scale [37]. Until now AM appears to be most economical for producing unique parts.

The idea has been already experimented for non-structural applications, like the work done by Skanska to print unique claddings. During construction there may be instances where delaying design and/or production of a part may be advantageous, such as customized parts built specifically for as-built dimensions. Similarly, there may be cases where components are lost or damaged and waiting on their replacements may cause construction delays. These examples are situations where "last minute" production of components on-site using AM can add value in construction.

6.4 Novel Forms

Architects started using AM of small-scale building models as a way to present a concept of their design to a customer. Through the advancements of large-scale AM, it is allowing architects to produce more complex interior and exterior geometries that would be difficult and costly to produce using conventional subtractive and formative processes.

Some have recognized that AM could start adding value to construction immediately, just by using it to print formwork with enhanced features such as functionality in the finished building, odd geometries, biodegradable materials, or reusability [26,27]. As an example, FreeFAB^{TM} Wax proposed printing moulds using wax material that can be created rapidly with low precision and can later be cut to the precise shape use milling techniques. Wax would act as the mould during construction, and then it could be heated to recover and reuse the material for other moulds.

6.5 Tolerance matching/correcting

Another potential application is the use of AM for tolerance matching. The construction industry is often faced with the challenge of having elements or modules on the construction site that do not have precise dimensions or sufficient tolerance for assembling them, requiring on-site modifications and complicating the assembly process. Matching issues with prefabricated components are due to the inability to maintain tight tolerances, introducing errors that propagate during construction that could risk the integrity of the structure [38,39]. AM brings the benefit of producing components with precise dimensions based on the design drawings, important for modular construction, and at the same time the ability to match tolerances in real time by printing customized connectors or infill as needed on-site.

7 Conclusion

Building-up elements from small deposits of materials using AM is having an impact in many industries, closing the gap of other manufacturing methods such as formative and subtractive processes. Aerospace, automotive, and other industries have explored the benefits of using AM in their day-to-day activities, finding new applications for different AM processes. The construction industry has become interested and has started exploring proof-of-concept AM applications that could be applied in the sector, looking to mitigate some of their current challenges.

Examples of AM technologies have been abundant, but it has been identified that most current work in the construction industry has been focused in material extrusion process using aggregate-based material for large-scale applications. Work with polymers have been effective for aesthetic purposes that have unique designs. Meanwhile AM applications using metallic materials for large-scale components is the least explored area due to its high cost.

Potential applications of AM such as optimized topologies, customized parts, in situ repair for construction in areas with limited access, and others, have been summarized and related to current AM technologies. These potential applications highlight opportunities in the construction industry that can be realized with AM. Interdisciplinary research is still needed to make AM a reliable and viable option in construction. To facilitate implementation of AM technologies and realize these potential applications, further work is needed investigating ways to print using multiple materials, to use in situ resources, and to combine AM with other processes as hybrid techniques.

This field is still in its infancy, without standardized testing and quality control to compare or benchmark these recent advancements. Furthermore, most of these early projects and AM technologies are often proprietary, lacking publically available, detailed information on their methodology and work, making comparison or evaluation of new AM technologies more challenging. While much work is needed to fully realize AM as a cost-effective and reliable option in the construction industry, the potential benefits it can provide are worthy of further research and development.

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