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Applications of additive manufacturing in the construction industry – A forward-looking review

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ABSTRACT

Additive manufacturing (AM), also known as 3D printing, fabricates components in a layerwise fashion directly from a digital file. 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 labor 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, and discusses related methods of implementing AM and potential advancements in applications of AM. Examples of potential advancements include use of multi-materials (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.

1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing, fabricates components in a layerwise fashion directly from a digital file. AM is a rapidly growing field that is having an impact on multiple industries by simplifying the process to go from a 3D model to a finished product. AM is unlike traditional manufacturing processes, such as formative processes that require the production of a mold to manufacture a product in mass quantities or subtractive processes that produce significant amounts of waste material as a solid piece of material is cut into the desired shape. AM can advantageously fabricate complex geometries with no part-specific tooling and much less waste material, filling a gap left by the other manufacturing processes.

Aerospace, automotive, and healthcare industries have explored the benefits of using AM in their businesses. Initial applications focused on rapid prototyping to reduce the time required to produce prototypes with complex geometries [1]. Since then, AM has evolved to include many types of functional end-use parts. Other industries, such as construction, are starting to follow the early adopters of these new AM technologies. Experimental applications of AM in the construction industry started appearing in the late 1990's [2]. These initial proof-of-concept applications helped identify potential benefits and challenges for AM technologies in construction.

This paper provides an up-to-date review of experimental AM technologies in construction, identifies the trends in AM processes and materials used in construction, 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 needs to be done in the future.

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2. Current construction industry and potential for AM technologies

To transform the current state of construction industry practice, innovations are needed in the way construction is performed. Challenges to construction include: work in harsh environments, decrease of a skilled workforce, safety during construction, production of large amounts of waste material, and transportation of materials to the site, among others [3,4,5,6]. The construction industry tends to be very fragmented. With a large number of specialized small and medium-sized construction firms, many are cautious to share advantageous knowledge or technologies with others, further stifling potential innovations in the industry [7]. These challenges and limitations to innovation are seen as opportunities for AM.

One prominent motivation for AM construction technologies is worker safety, particularly in extreme environments [8]. When construction in harsh environments is unavoidable, the difficulty and risks increase, adversely affecting construction quality and human safety. For example, working in freezing temperatures may present challenges in excavation or concrete pouring, environments with very high temperatures could cause dehydration to construction workers, and sites with exposure to chemical or nuclear contamination may pose serious human health risks [9]. A solution used to address such issues has been off-site fabrication, where parts and assemblies are delivered to and assembled on-site, reducing the amount of on-site labor and often increasing construction quality and consistency. 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.

Another opportunity for AM involves shrinking the supply chain, particularly for parts that need expedited delivery. AM allows customized parts to be printed on-demand from a 3D model without significant lead time. Using AM in construction could reduce the number of steps involved in the supply chain, bringing the supplier closer to the customer [10,11]. 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. This alleviates productivity problems caused by late deliverables to the job site, which are known to have several deleterious effects to productivity and safety, such as working out of sequence [12].

Another motivation for AM is decreased availability of a skilled workforce. Contractors are finding it challenging to recruit a workforce with the necessary skills (e.g., experienced carpenters, heavy equipment operators, welders, and fabricators) [13]. The use of AM in construction should lower the demand for skilled craft while at the same time opening new opportunities for jobs with different skill sets than are in current practice.

Another potential benefit from AM is the reduction of formwork (and related temporary structures) used during construction. Concrete structures are commonly built using temporary formwork to maintain the desired shape of fresh concrete as it hardens, and formwork labor and material costs range from 35 to 60% of the overall cost of concrete structures [14,15,16]. The most common formwork is made from wood, using subtractive processes to cut it to the desired shape, producing waste material before it is even used. In the 19th and 20th centuries, formwork was produced for a single use only [14]. Currently, to decrease the cost of formwork and reduce material waste, formwork is being reused. Reducing formwork use not only reduces waste material produced during construction, which is considered to be about 23% of the total material wasted in construction [2,17], but it also reduces the cost and time associated with placing and disassembling the formwork, largely by removing the need for formwork for direct placement of the construction materials. An alternate approach is to use AM techniques to fabricate the formwork – a recent practical example is using AM deposition of wax to create molds for precast concrete components that can be melted and reused [18].

Whether through design of complex forms or by direct deposition of final materials, AM techniques also allow architects and designers to produce complex interior and exterior geometries that would be difficult (or impossible) and costly to produce using subtractive and formative processes. This potential benefit offers opportunities for new designs and forms, giving more freedom to architects, without affecting the complexity and productivity during construction [6,19].

Safety, reducing needs for skilled workers, replacing traditional supply chains, waste reduction, and new geometries are but a few of the potential applications for AM in construction, motivating further review of AM technologies and their possibilities.

3. Additive manufacturing processes

To understand the advantages that AM could bring to construction, it is important to understand the different AM processes. 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:

- Vat Photopolymerization – 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 Hull in the 1980's and commercialized first by 3D Systems [4,20,21].
- Material Jetting – A process of selectively depositing drops of material in a layerwise fashion. An example of this process is PolyJet technology from Stratasys [21].
- Binder Jetting – 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) [21].
- Material Extrusion – A process of extruding material through a nozzle and depositing it layer-by-layer onto a substrate. The process was invented by Crump and commercialized by Stratasys as Fused Deposition Modelling (FDM) [21], but it now forms the basis for a very wide variety of inexpensive personal 3D printers.
- Powder Bed Fusion – 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 [21]. Direct Metal Laser Sintering (DMLS) [21,22] and Selective Laser Melting (SLM) are common versions of powder bed fusion for fabricating metal parts.
- Sheet Lamination – 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 [21]. Ultrasonic Additive Manufacturing (UAM), commercialized by Solidica Inc. fabricates metal objects using ultrasonic welding [21].
- Direct Energy Deposition – 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 [11,21], which is particularly useful for repair of damaged metal parts [23].

Although all of these processes have been explored in many different industries, AM technologies in the construction sector are in the earlier stages of development and innovation diffusion, with initial applications primarily focused on material extrusion processes for large-scale components.

4. AM in construction

Table 1 presents examples of AM technologies used for construction