3D Printed Structures: Challenges and Opportunities

By Caitlin T. Mueller, Ph.D.

Technologies for 3D printing, or more broadly additive manufacturing, have proliferated in recent years, and have captured the public's imagination as a revolutionary way to democratize small-scale, customized manufacturing for the DIY community. In the design of buildings and bridges, 3D printing has proven to be a valuable technique for creating intricately detailed scale models in a fraction of the time required by traditional methods. In both cases, the generalized layer-by-layer material deposition process is a compelling way to achieve geometries of nearly infinite complexity with ease.

But 3D printing has also permeated markets beyond the consumer and model scale, with increasing buzz about applying the technology to large objects, such as full-scale buildings. This prospect is exciting for several reasons: reduced construction waste through highly precise material placement, increased capacity for complex geometries for both functional and aesthetic purposes, and new possibilities for integrating building component functions into a single, streamlined assembly.

Recent developments internationally have provided increasing evidence that such advantages can be realized, and that 3D printing may represent a viable pathway for the future of construction. For example, at the University of Southern California, researchers have developed Contour Crafting, a robotic fabrication system that uses a large-scale gantry to deposit a low-slump concrete-like material in layers to produce vertical wall systems and structural elements for housing [Khoshnevis, 2004]. This technology has also garnered interest from NASA as a way to construct habitats on the moon and Mars using mostly local materials. A similar technique has been used by a Chinese company, Winsun, to produce several housing units, produced in parts and then assembled on-site, including a five-story apartment building [Stampler, 2015].

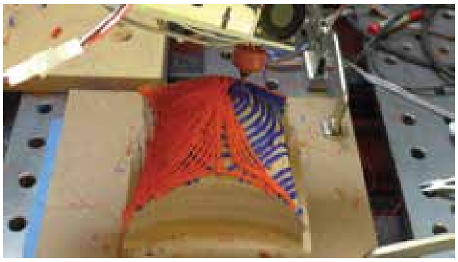
In the Netherlands, DUS Architects and collaborators are building a full-scale 3D-printed replica of a traditional Amsterdam canal house, using a custom-made, room-sized 3D printer (called the *KamerMaker*, or "room maker") that deposits an extruded, heated thermoplastic material [Wainwright, 2014]. As a scaled-up version of commercially available printers like those from MakerBot and Ultimaker, this technique can produce double-layer walls and other components with compelling geometric variation, allowing for storage and furniture to be integrated, and for acoustical and structural properties to be tuned.

Most recently, Skidmore, Owings & Merrill (SOM) and the U.S. Department of Energy's Oak Ridge National Laboratory produced a small, transportable 3D-printed habitat with integrated photovoltaic panels, printed using ABS plastic reinforced with 20% carbon fiber and post-tensioned with steel rods [SOM, 2015]. The printing technique produced the building in 2-foot wide wall and roof sections that integrated structural and building envelope functions, acting as vacuum-insulated panels for thermal insulation.

3D printing is also being investigated at the component scale for buildings. For example, Arup developed and produced a customized 3D printed steel structural connection for a tensile structure, using topology optimization to generate complex, highly efficient forms that are responsive to the specific forces at each node [Galjaard et al., 2015]. With a 3D printing technique called direct metal laser sintering, which selectively melts and fuses metal powder with lasers in a layer-by-layer approach, a stainless steel component was produced that weighed 75% less than a conventional plate-based version.

These advances offer compelling support for a new vision of construction for civil structures. However, several key challenges remain to be met before these techniques can be used in a widespread, cost-effective manner, especially in terms of structural behavior and performance. There is an exciting and important opportunity for the structural engineering community to have a strong voice in the further development of these new techniques to ensure that safety and material efficiency are prioritized.

One set of challenges relates to the materials and composites proposed for 3D printing of civil structures, many of which are new to this application or new in general. While a great deal is known about traditional structural materials such as steel, concrete, and timber, the behavior and properties of materials produced through heated extrusion, layered deposition, and sintered powders are less well understood, and need to be studied and developed with long-term building applications in mind.



A new 3D printing technique developed at MIT, called stress line additive manufacturing (SLAM, deposits material along lines of principle stress instead of in layers to maximize structural performance.

Furthermore, the layer-by-layer fabrication approach should be reconsidered for applications with structural functions. In many materials and techniques, this leads to significant anisotropy in strength and ductility, due to poor bonding between layers, limiting the efficacy of printed parts. Current research at MIT's Digital Structures research group offers one alternative: a new process called stress line additive manufacturing (SLAM) uses a robotic arm to deposit material along three-dimensional lines of principal stress, ensuring material connectivity in the most critical directions [Tam et al., 2015] (see *Figure*).

A final set of challenges relates to the question of formwork. While 3D printing promises to reduce or eliminate construction waste, the difficulties of supporting a structure as it is constructed remain for geometries that cannot be fabricated as vertical extrusions. Small-scale 3D printers address this problem by printing support structures concurrently with the final objects, which can be dissolved or detached once the print is complete. A similar approach could work at the building scale, but more research is needed to determine how to implement this effectively, ideally in a way that involves re-usable or recyclable support material.

Looking forward, it is clear that many such challenges lie ahead before the promise of 3D printing can be broadly achieved for building structures, but the recent, rapid development of increasingly realistic proofs-of-concept is highly encouraging. The continued contributions of pioneering structural engineers are critical to help push this transformative technology from small-scale geometric representation to high-performance, full-scale structures.▪

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