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Using 3D printing for Ultra High-Performance Concrete in Construction Industry

Aditya Sunil Yadav
Sr. Project Engineer, STABIL Concrete Products LLC

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I. Introduction

3D printing is a booming industry that has brought manufacturing to an entirely new level. From automobiles to aerospace, and food to body parts/organs, 3D printing is delivering amazing results. It's application in the construction industry is still in its infancy compared to other industries.However, 3D printing technology has been extensively researched academically, and is slowly transitioning from experimental to large-scale construction. The technology can be easily used for printing building components and precast concrete elements. The challenge lies in using the technology for printing entire structures complete with reinforcement, which are compliant with all the requirements of a regular building. 3D printing of structures can address many issues related to the construction industry such as worker safety, material wastage, sustainability and greenhouse gas emissions. In addition, it eliminates the need for formwork, which is found to be about 70 to 80% of the total cost of construction. With the increasing demand for more sustainable building solutions, 3D printing can offer a unique opportunity to meet the demands and also keep the cost of construction in check. One of the most challenging issues in the 3D printing technology for concrete is the placement of reinforcement into the matrix. The use of ultra-high-performance concrete (UHPC) addresses this issue to a certain extent as it utilizes metallic or non-metallic fibers in place of rebars. UHPC also uses very fine materials in the matrix that are easy to extrude. This paper takes a look at the different types of 3D printing technologies used in construction and the use of UHPC for building architectural precast elements for façade applications.

Keywords: UHPC, Concrete, Precast, Façade, Manufacturing, Fibers, 3D Printing

Significance of 3D Printing in the Construction Industry

The construction industry is one of the most important industries in the world as it provides much needed protection from the elements of nature. Whether for shelter, office, manufacturing or recreational activities, this industry provides the shell that houses everything that runs in this world. It's no wonder then that the most widely used material on the planet is concrete. However, there are several significant challenges that this industry faces such as:

- High cost – Formwork itself takes up a huge chunk at about 80% of the total concrete construction cost **[1]**
- Slow construction speed–The various steps involved in construction starting from material procurement, transportation, formwork installation, concrete pouring and curing are all time-consuming processes
- Safety issues – The construction industry has a woeful safety record. According to the U.S. Bureau of Labor Statistics (BLS), the construction industry accounts for only 6% of the workforce in the country but accounts for 20% of workplace fatalities. Of these falls account for 34% of deaths, others being struck by equipment, caught in between, and electrocution **[2]**
- Design limitations – Concrete is cast using formworks, which are rigid and limit geometrical freedom in designing structures. To make exquisite designs, the formwork has to be customized, for which a high cost has to be paid. Rectilinear formworks also limit an architect's creativity and are structurally weaker due to stress concentrations compared to curvilinear forms
- Waste generation – The construction industry is a leading contributor to the amount of waste generated, about 80% of the total waste in the world **[3]**. A significant source is formwork, which though it can be reused for a few times, ultimately

has to be discarded due to wear and tear and loss of strength.

- Sustainability – With the increase in environmental policing, construction companies have to make sure that the material they use and the construction methods they employ are environmentally friendly and sustainable. Since the entire construction process is energy intensive and emits greenhouse gases, this is a major issue facing the construction industry.

3D printing technologies can help mitigate these problems to a certain extent and hence is gaining popularity. In the past few years various 3D printing technologies have been studied and experimented with and its use is significant for the construction industry.

Additive Manufacturing (AM)

Additive manufacturing, another name for 3D printing, is used for 3D fabrication of structures from a digital model in layers that results in less material wastage.AM is defined by the International Committee F42 on AM Technologies of 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***[4]**." This technology has already been successfully applied in various industries such as automobiles, aerospace, biomedical, food manufacturing, etc.

The application of AM in construction was first attempted by J. Pegna**[5]**using cementitious materials in which he glued sand layers together with a paste of Portland cement using an intermediate process. 3D concrete printing uses digital technology and new developments in material technology to construct concrete elements without the use of expensive formwork. This will give architects the required freedom to construct any shape that is structurally sound and free from the usually rectilinear design, characteristic of formwork. Some advantages of using 3D printing in construction include:

- Elimination of formwork thereby reducing cost of construction and also reducing wastage of material
- Reduction in time required for construction as 3D printing technology will operate at a constant rate
- Reducing error as material deposition will be extremely precise, also reducing material wastage
- Providing architectural design freedom to designers to express creativity with sophisticated designs
- Increasing the safety level in construction by eliminating dangerous jobs like working at heights

Principles Behind 3D Printing Technology

The basic principle of 3D printing involves digitally reducing a three-dimensional volume into a series of two-dimensional layers. These individual virtual layers are then builtupwith each layer being successively cast into the final product. There are two main techniques on which this technology is based:

1. Extrusion based technique

The extrusion-based technique is similar to the fused deposition modelling (FDM) technique in which cementitious material is extruded layer by layer from a nozzle mounted on a six-axes robotic arm, crane or gantry. The technique can be used for on-site large-scale construction applications for components having complex geometry. Different types of extrusion-based 3D printing include:

a. Contour crafting – Developed at the University of Southern California, the technology is designed to extrude two layers of the cementitious mix to create a vertical concrete formwork. It requires manual insertion of customized reinforcement ties between layers as the machine continues to extrude layers. Reinforcement is put at every 13 cm in the vertical direction and at every 30 cm in the horizontal direction. The surface of the extrusion is smoothed by trowel-like fins attached to the head of the 3D printer. When the formwork is complete, the first batch of concrete is poured up to a height of 13 cm. The next batch is poured after one hour to allow partial hardening and curing of the concrete to control the lateral pressure**[6]**. However, this technology is only limited to vertical extrusion and the initial formwork system can be complex to implement for production. In addition, the concrete is cast within the formwork with a gap of about an hour, which can result in weak interfacial zones between layers.

b. Concrete printing – Developed at the Loughborough University in the United Kingdom, this technology is similar to the contour crafting technique but has a smaller deposition resolution, which allows for more precise control over the geometry. The material used for this technique is high-performance concrete with fine aggregates and reinforced with fibers, similar to UHPC. This results in superior properties in the final product compared to contour crafting. Voids can be carefully integrated into the design to form conduits for later placement of reinforcement. The method requires additional support to create overhangs requiring the use of a second material and additional deposition device**[7]**. The process is quite slow when considering its industrial application and the use of second material increases cost and reduces efficiency.

c. On-site 3D printing – In TU Dresden, Germany, a technology has been developed that will allow 3D printing at site. It is designed to have greater geometrical flexibility, uses regular construction machinery and lesser dependance on skilled labor. Known as CONPrint3D, it uses existing techniques and machinery and is able to adapt to constraints at site. It utilizes a concrete boom pump fitted with a customized print head to accurately reach and deliver material to hard-to-reach positions **[8]**.

d. Large Scale 3D Concrete Printing using UHPC – UHPC uses very fine aggregates and fibers as reinforcement, which makes it ideal for use in 3D printing technology. The idea was developed on by a team in France and uses the extrusion technology with the six-axes robotic arm to deposit UHPC in layers. The technology will allow for the production of large-scale elements with a complex geometry without using supports. It uses the tangential continuity method for slicing to create layers of varying thickness that are structurally sound. It also does not require a gantry frame or crane but relies on the robotic arm**[9]**.

Some examples of extrusion-based 3D printed structures are:

1. The 3D printed Villa by HuashangTengda

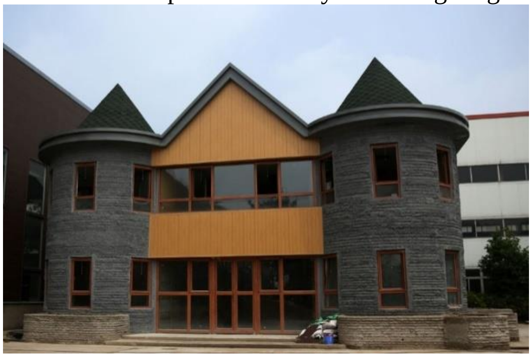

Image courtesy: https://www.thestructuralengineer.info/news/this-two-story-3d-printed-villa-was-constructed-in-just-45-days

2. 3D printed concrete beam

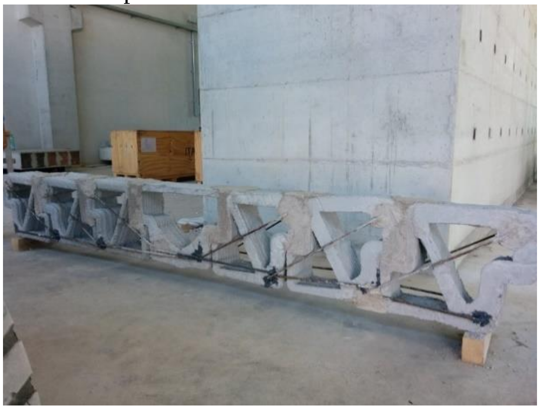

Image courtesy: https://www.3dwasp.com/wp-content/uploads/2015/08/3d-print-concrete-62.jpg

3. Y Box Pavilion

Image courtesy: https://www.buildernews.in.th/wp-content/uploads/2016/08/Y-BOX-pavilion-21st-C.-Cave-3-e1472184204261.jpg

4. 3D printed house by Apis Core

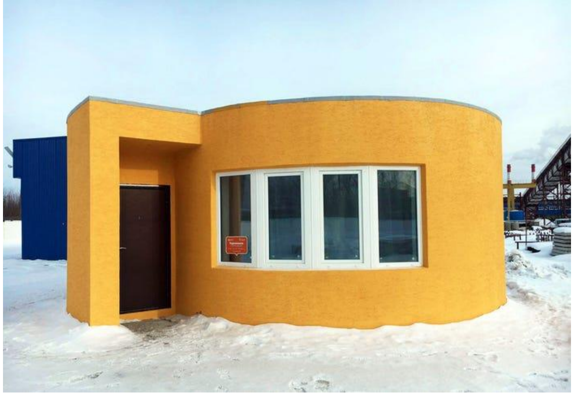

Image courtesy: https://i.insider.com/58d3ebc8112f7048008b6571?width=700

5. Powder based technique

The powder-based technique is designed for manufacturing precast elements off site. It is great for manufacturing components like panels, interior structures and permanent formworks, which can be later assembled on site. The technique creates structures by depositing a binder liquid into a powder bed. The liquid binds the powder in the location where it impacts the powder bed. A roller, mounted with a printhead spreads a 3mm thick powder layer to cover the build plate base. A thin layer of powder about 0.1 mm thick, as set in the 3D printer, is spread over the base layer and smoothed with the roller. Next, the binder feeder delivers the binder solution to the printhead, which selectively jets it on the powder layer. Wherever the binder solution falls, the particles of the powder bind with each other. After the built part is complete, it is allowed to dry and the loose powder is removed with an air blower.

a. Emerging Objects – This technique deposits a binding agent selectively to harden a proprietary cement composite mixture. The technology was used to manufacture the Bloom, comprising of 840 3D printed blocks**[10]**.

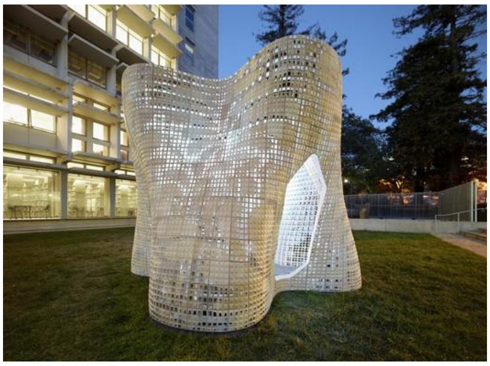

Image courtesy: https://www.archdaily.com/613171/emerging-objects-creates-bloom-pavilion-from-3-d-printed-cement/5512d6d5e58eceefc00000f2-rael_san_fratello-bloom-0378-jpg

b. D shape – Developed by Enrico Dini, it selectively hardens a largescale sand bed by depositing a binding agent. Sand is used as the build material and sorel cement (magnesium oxychloride cement) is used as the binding agent**[11]**. The Radiolaria pavilion was made with complex geometry using this method.

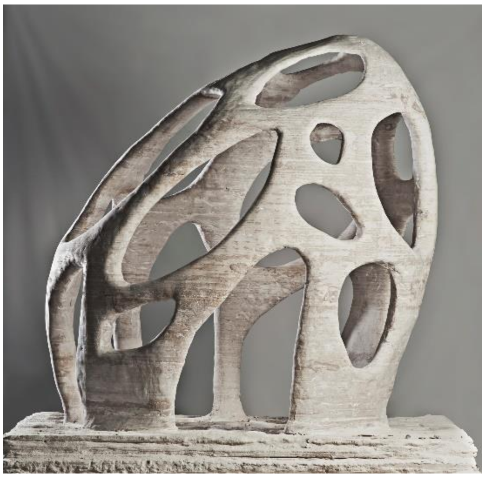

Image courtesy: https://d-shape.com/Prodotti/the-radiolaria-pavilion/

The Desirable Properties of UHPC

UHPC has gained significant momentum in the construction industry owing to its superior performance compared to traditional concrete and is known for its exceptional strength and durability. UHPC exhibits low permeability and displays elastic-plastic or strain-hardening characteristicsunder uniaxial tension.

UHPC differs from regular concrete especially in its use of fine high-strength steel fibers that impart the strength of steel without the bulk of reinforcement bars. Fibers used in UHPC include carbon steel, high carbon steel, polyvinyl alcohol (PVA), glass, or a combination of these. Fibers impart the required ductility to mold the concrete into any desired shape, which is a desirable characteristic for components of architectural design.

The components in the UHPC mix are typical of any concrete mix such as Portland cement, fine sand, accelerators, chemical admixtures, and water. These ingredients are however optimized in a UHPC mix to obtain low porosity and ductility. This gives it the ability to deform and support flexural and tensile loads even after initial cracking. Compared to traditional concrete, UHPC is more comparable to steel**[12]**, requiring 70% less material to achieve the same structural requirements.

UPHC with metallic fibers has compressive strengths between 18000 to 36000 psi or 150 to 250 MPa. UPHC with non-metallic fibers has compressive strengths between 11500 to 18000 psi or 80 to 125 MPa. It has a high cement content, about 800 to 1200 kg/m^3, superplasticizers, fine sand, steel fibers and an ultra-low water-binder ratio ranging between 0.15 to 0.25, making for a dense microstructure.

The research on UHPC has increased significantly since the time it was introduced. It is a trending topic in the field of civil engineering, especially the material design and manufacturing aspect. Material design is the optimization of mix proportions by varying ingredient to produce proprietary mixes based on engineering requirement. Some examples of such research are**[13]**:

- Employing compressible packing model by which a mix could be developed with compressive strength exceeding 150 MPa
- Designing sustainable UHPC by achieving maximum wet packing density using new methods such as response surface method (RSM) and D-Optimal design (DOD)
- Improving flexural strength by adjusting fiber orientation through casting parameters such as casting length, casting height, mixture viscosity and direction and distance of flow
- Improving early strength by studying the effects of curing temperatures at 10, 20, 30 and 90 degrees Centigrade, and other curing regimes such as microwave curing and carbonation curing

The Use of UHPC For 3D Printing

Creating intricate geometrical or abstract designs using UHPC is a popular trend in the architectural world. The use of UHPC in architectural components significantly reduces the number of sections and eliminates the need for passive reinforcement. It is possible to design highly durable and sustainable cantilevered structures and ultra-thin UHPC elements.

The ductile property of UHPC allows for the design of curves with tighter radii**[14]**. It also for the design of creative colored and textured decorative wall panels, latticed and perforated panel systems, interior décor of all styles, surface finish imitations such as stone, glass and oxidized metal, 3D lattice shapes, etc.Some examples of architectural UHPC installed around the world are:

- MuCEM - The Museum of Civilizations in Europe and the Mediterranean, features a UHPC lattice facade, roof and footbridge
- The Atrium, Victoria, B.C. features an ultrathin unitized curtain wall system.
- The Community Center, Sedan, France features perforated UHPC panels creating a double-skin facade that provides daylight, shade, and privacy
- Stade Jean Bouin, a 23000 square meter UHPC lattice envelope and roof
- The RATP bus center in Thiais, France features a unique LEGO-style textured skin

However, making these designs requires extensive use of formwork of different materials and is time consuming. Intelligent design, i.e., utilizing automated machinery to mix, cast and cure UHPC using 3D concrete printing is being popularly researched. The AM technique allows printing of successive layers without the use of excessive labor and formworks. By bringing together the superior properties of UHPC and 3D printing technology, researchers have been able to develop 3D printed UHPC. Researchers are also trying to utilize the properties of UHPC using powder-based 3D printing.

Apis Core has utilized hardened 3D printed UHPC as reinforcement in normal concrete. It was found that the printed UHPC acts almost like a steel rebar and improved the bending capacity inside the concrete. It was found that the flexural strength increased by 160.5% with the use of UHPC as reinforcing element **[15]**.

3D printing of UHPC elements can be very advantageous for the manufacture of complex geometrical facades, especially since it will eliminate the need for formworks. UHPC possesses high compressive strength and hence enables size efficiency to print concrete elements with thin cross-sections. The installation of reinforcement bars in conventional concrete poses a significant challenge to the 3D printing technology. Since UHPC utilizes short fibers as reinforcement and lends high flexural strength and fracture toughness**[16]**, it is an attractive alternative for constructing 3D printed concrete elements.

Another research conducted on the flexural performance of UHPC showed that 3D printed specimens showed greater flexural performance in the printing direction compared to specimens cast in a mold. This was attributed to the alignment of the short steel fibers in the direction of the print in comparison to the random orientation observed in those cast in molds **[17]**. Since flexural or tensile stress acts in a specific direction, the random orientation of the fibers can reduce the efficiency of the reinforcement imparted by the fibers as they are dispersed in various degrees of freedom.

In order to influence fiber orientation in mold cast UHPC, various factors have to be tailored such as the rheological properties of the matrix, mixing procedure, formwork geometry, casting method, casting time, etc. In the case of extruded fiber reinforced composites, fibers tend to align in the direction of the extrusion during the extrusion process due to the high shear and compression forces in action. The orientation and distribution of short fibers can be influenced by parameters such as rheology, fiber type, fiber content, geometry of the nozzle, and speed of printing.

As mentioned before, 3D printed UHPC was used by Apis Core as reinforcement in regular 3D printed concrete. This method can bring significant improvement in the load-bearing capacity of 3D printed concrete. This process requires a dual 3D printing procedure where UHPC acts as the inner core and is enveloped by regular concrete and then extruded together. However, there may be discrepancy in parameters such as height of deposition layer, deposition rate and speed of printing, which may result in the heterogeneity of the composite materials, negatively affecting the mechanical strength of the element. 3D printing UHPC maintains the high compressive and tensile strength of mold cast UHPC in addition to a more appropriate fiber orientation, making it ideal for use as reinforcing material for 3D printed concrete.

II. Conclusion

The use of 3D printing of concrete is no longer a pipe dream but is being currently pursued with great expectations for the future of construction. Since construction projects are cost, material and time intensive, better methods of construction are the need of the hour. With the push for the use of sustainable materials and green energy, 3D printing technology holds a promising future for construction. 3D printing can eliminate the need for formwork, which is a major contributor to the cost of a construction project and also to the waste produced. 3D printing eliminates the need for formwork, significantly bringing down cost and the need for skilled labor. UHPC is the material of choice when it comes to 3D printing as it addresses a major challenge to the 3D printing – the use of reinforcement bars. Since UHPC uses fibers as reinforcement, the prospect of using UHPC is wide. Architectural facades with complex geometry can also be printed using UHPC, however more research is required for the proper implementation of these techniques into the construction industry, especially for large scale projects.

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