ABSTRACT

Additive Formwork explores the potential and advantages of 3D printed, flexible formwork for precast concrete architectural applications. This research experiments with 3D printed malleable polymers as a mold at both a small and large scale, to determine the limitations and opportunities for architects and designers in construction. This paper describes the background research, concept, fabrication process, materials, methods and conclusions of this work in progress.
INTRODUCTION
3D PRINTING AND CONCRETE

Currently, several architects and engineers (Khoshnevis 2006; Buswell 2006) are focused on 3D printing large-scale concrete structures for architectural applications using a FDM (fused deposition modeling) technique of printing directly with concrete-based materials. However, Additive Formwork investigates a completely different approach to 3D printing at the scale of architecture. Rather than directly printing building sections in concrete, whose structural capabilities are in question, flexible formwork can be 3D printed and used to cast concrete with traditional methods. This new formwork could shorten the process of prefabricating concrete, while offering highly detailed surface finishing and an expanded degree of geometric freedom.

PRECAST CONCRETE

Additive Formwork applies research from standard 3D printing techniques to a conventional building fabrication process: precast concrete. It poses the question: can 3D printing formwork for concrete alleviate some of the problems associated with traditional casting by reducing fabrication steps and increasing geometric flexibility?

Precast concrete consists of concrete (a mixture of dry cement, aggregate and often admixtures, which hydrolyse when water is added) that is placed into a form or mold, typically made of wood or steel. The concrete is then cured before the form is stripped and either disposed of or reused. When plant-cast, this process is completed at a location other than its final in-service position, to allow for precise fabrication in a controlled environment, and the final units are then transported to the construction site for erection into place (Simmons 2001). Formwork for complex geometries is time and material intensive to construct so efficiencies are used to control costs, such as maximizing the number of castings per mold (Clark Pacific, 2000). Recently, several groups have been researching fabric as an alternative to traditional formwork (West 2009) to form precast concrete panels, however it has limitations in form, texture, and perforations.

Historically, casting custom textures and intricate patterns in concrete relied on creating a mold from an existing object. For example, if a wood grain texture was desired, strips of wood were used as a mold, allowing the concrete to be imprinted with the grain. However, over the past few decades new fabrication techniques have emerged that allow the casting of complex geometries or offer a wide variety of textured finishes for what were traditionally flat and unadorned surfaces. One of these techniques is the use of 3D printing.
of CNC milling machines to create form liners and molds. Rigid foam or other solid material is sculpted to create the positive of the form, which is then cast in a flexible material, such as silicon (Bell 2012). There are several companies, such as Architectural Polymers, that specialize in providing CNC milled flexible form liners for the construction industry. Additive Formwork reconsiders this process, eliminating the initial step of sculpting a positive and consequently the associated labor and material costs, to print the form directly.

MATERIALS:

PRINTING MATERIALS

New 3D printing materials are currently being developed and released at a rapid pace. Flexible plastic filament was recently introduced to the desktop 3D printing market and this project seeks to explore its potential in creating flexible molds for concrete (Figure 1). The advantage of this material over standard rigid plastic is that a single formwork can be recast multiple times with no damage to the mold itself. Flexible molds hold their form during the casting process, but then allow the concrete to be easily released.

There are multiple manufacturers currently offering 3D printing filament with varying degrees of flexibility (Table 1) and they are all being tested to determine their individual characteristics, efficiency and success in this system. In initial testing, the Flex EcoPLA™ filament has generally performed well during casting, however the printing speed (15mm/s) is less than half that of printing with a standard PLA filament (50mm/s), slowing down the overall fabrication time.

CASTING MATERIALS

Experimentation thus far has been with mortar mixtures (sand, cement, and water) that have no additives or composite materials added to the mixture. Since the initial molds have been at a small scale we have not been able to use concrete mixtures (sand, gravel, cement, and water), however as the system is scaled up, this limitation will be overcome. Other materials are currently being explored and tested, such as Glass Fiber Reinforced Concrete (GFRC) and Ultra High Performance Concrete (UHPC). These materials offer the potential of creating thin, detailed panels that have structural integrity without additional reinforcement.

PARAMETRIC DESIGN

This project has combined the design and fabrication parameters into a single parametric design definition, allowing for the quick development of design iterations. The geometry for the prototypes was developed within Rhino’s parametric scripting language, Grasshopper®. The initial step of the Grasshopper® definition defined the overall form of the application, for example a wall panel, by inputting the design parameters of the desired structure. When using a desktop 3D printer, a slicing program was then used to simulate the movement of the printer and generate the tool path code. For the robot arm, the Kuka PRC plugin was used to simulate the movements and generate the code of the tool path (Figure 2). These simulations are necessary to identify any possible errors prior to fabrication, such as avoiding severe overhangs from one layer to another that can create imperfections in the mold. Currently, the master Grasshopper® script includes the basic design and fabrication data, however, it does not include all the possible inputs that could inform the final design, such as structural performance and the design of the reinforcement.
FABRICATION PROCESS

The first step in the fabrication process is 3D printing the flexible formwork. Research has been carried out using both small and large FDM style plastic extrusion system 3D printers (Table 2). We started the project on a small-scale printer (Figure 3), and were quickly able to identify the opportunities and limitations of the material and fabrication system. At a larger scale, we have been using a commercially available large desktop 3D printer (Figure 10), as well as a six-axis robot arm. The robot arm has a customized plastic extrusion head end effector attached, which has been used to prototype full-scale panels up to 6ft in diameter (Figure 4). Since the extrusion nozzle on the robot arm is larger than both desktop 3D printers, prototypes can be printed in much thicker layers, reducing the overall print time.

Once the print is complete, a release agent is applied to the mold and then the material is mixed, placed, and left to cure in the mold (Figure 5). Once the concrete is set, the flexible mold is simply removed and ready for another casting. At the moment, we are not utilizing reinforcement in the cast, but that will be included in future large-scale prototypes.

PROTOTYPING

Creating a direct link between the digital models and physical tests is essential for Additive Formwork, since the 3D printing material and casting method are experimental. Optimal printing parameters can only be determined through physical prototypes. The following factors were examined when prototyping: structural stability, permeability, printing speed, and surface delineation. For example, a key factor that was discovered during the design-to-fabrication workflow was that subdividing the overall surface was necessary to not only avoid warping (Figure 6), but also create a stiffer wall surface during the casting process.

The surface finish of the concrete is directly related to the 3D printing layer height. For example, when printing with desktop 3D printers, a layer height of .1mm has been used, creating a relatively smooth surface finish, with the printing process almost undetectable (Figure 9). However, the surface finish for molds created using the robotic arm was slightly rougher, since the layer height was set to 1.8mm. Therefore, as the printing layer is scaled up, the overall print time is reduced and the imprint of fabrication system is revealed.

There are challenges posed by this technique that will be addressed as the research continues. One of these is creating a watertight mold for casting. Thus far, the molds have been
impermeable except for at the base of the print, which sometimes allowed water to slowly seep through the bottom. While this has not hindered the casting process, it will be addressed to allow for precise curing. The durability of the formwork during the casting process also merits further experimentation, as stresses put on the molds include the placement of reinforcement and the use of release agents. To date we have cast several molds up to five times and have seen very limited damage to the mold, however this will continue to be monitored.

DESIGN

Several designs are being tested and they can be segmented into two categories. The first are interlocking blocks (Figure 7) that have intricate exterior patterns and are intended for wall or roof applications. The blocks are currently fabricated with a single mold (Figure 11b), however they could also be fabricated using a multi-part mold (Figure 11c). The interlocking joint would be achieved with a vertically slotted connection to hold each block together (Figure 12).

The second design category is wall panels, which include both solid and perforated panels. The solid wall panels are intended for wall veneer applications and the prototype designs study the various patterns and effects that could be applied (Figure 8). The casting technique for these panels is similar to that used for form liners (Figure 11a). The perforated panels focus on shading devices that could be used in rain screen applications (Figure 8) and various geometries were developed to test their feasibility. For example, we are currently developing on an interlocking perforated wall panel that reacts to the sun (Figure 13), where the size of the aperture varies based on its sun orientation, as well as the desired interior shading performance.

ONGOING RESEARCH

Additive Formwork began with research into both the printing and casting material with the goal of identifying important parameters to create a reliable fabrication system. We are currently establishing connections with industry partners, such as precast panel fabricators and manufacturers of high performance concrete materials (UHPC and GFRC) to verify the system’s viability and find collaborators for larger scale production. To scale up the technology there are a few main parameters that are critical to study:

1) Scaling up the printing process (size of the 3D printer and print bed);
2) Testing the durability of the molds during routine casting;
3) Casting with concrete with course aggregates; and
4) Incorporating additional bracing into the design to withstand the hydrostatic forces, especially flat wall sections.
This research could lead to several interesting paths of investigation. For example, the inherent flexible nature of the material and related surface warping that can occur during the printing process could be considered an opportunity and exploited, similar to what has been done with fabric formwork (West 2009). Further research can also be carried out related to the use of parametric models. We hope to build upon the knowledge from other projects that have studied the parametric design possibilities for precast panels (Bell 2012) and structural precast systems (Raspall, Imbern and Choi 2013). Since our current research has solely focused on single molds, we are also investigating how to design and implement two-part molds to cast large and complex geometries (Figure 11c).

Additionally, we are currently testing the viability of recycling 3D printed, flexible formwork at the end of its usefulness. The process starts by washing the mold and removing any residual materials that may have adhered to it during the casting process. Once cleaned and dried, the mold is then shredded into small pieces (no larger than 5mm on any side), which are fed into an extruder for 3D printing. The biggest challenge is to fully clean the plastic and remove all unwanted particulates, since this has been known to clog the extrusion nozzle and affect the quality of the recycled plastic.

CONCLUSIONS

Additive Formwork offers a new pathway for 3D printing to improve an aspect of architectural construction. Unlike directly 3D printing a structure, this method has the potential to be implemented immediately into the construction industry because it improves upon an existing, well-understood technique and material (precast concrete).

REFERENCES


IMAGE CREDITS

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