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Fabrication of Topology Optimized Concrete Components Utilizing 3D Printed Clay Mould

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Abstract

This paper presents the result on the development of an additive manufacturing approach to fabricate topology optimized concrete components, discuss the challenges associated with the clay mould printing process and its assembly. Our intention is to improve the fabrication process that increases efficiency without losing accuracy. We introduce a prototype of a concrete shelf to access the ability of such process in fabricating large-scale artifacts. We believe steps towards advancing the fabrication process of clay mould will accelerate its application in concrete manufacture.

Keywords: Clay Mould, Robotic Fabrication, Additive Manufacture, Topology Optimization, Concrete.

1. Introduction

In the past two decades, the principles of Additive Manufacturing (AM) with cementitious material have been substantially developed to manufacture freeform concrete components. These AM techniques, for example, Contour Crafting - concrete extrusion AM [1] and D-shape project - concrete binder jetting AM [2] present advanced options to concrete construction leading to high production rate, more geometry freedom and cost reduction [3].

One of these techniques introduces a robotic technology to fabricate clay moulds via AM extrusion, for the casting of freeform concrete components using Self Consolidating Concrete (SCC) [4]. Its manufactural process is similar to other mould production which involves fabrication of mould segments, assembly, casting, demoulding and post processes. Once the concrete cures, the clay is demoulded and can be recycled for subsequent prints. Thus, this method takes advantage of AM to enable the production of freeform geometries and the recyclability of clay to overcome the wastage of extensive one-off formworks.

In this paper, we apply the AM clay technique to fabricate freeform topology optimized concrete components. Our main research objective is to develop a fabrication process which is suitable for designated geometry that improves the fabrication efficiency without losing the accuracy. We firstly introduce the design and fabrication of a concrete shelf as a prototype. In addition to the overall fabrication procedures, we present the fabrication of hollows with various cross-section topologies. This further contributes to the expansion of achievable geometry range which offers the flexibilities in terms of AM clay with more geometrical varieties. At last, we discuss the result and our future development.

2. Topology optimization

Topology optimization is no longer a novelty in architecture and civil engineering since the first discussion by Bendsøe & Kikuchi [5]. It can be used in structural design to reduce the material consumption of elements, allocating matter only to the areas where it is required. The resulting parts are highly material-efficient, but their geometry is usually highly complex. Therefore, the feasibility of such efficient structures is limited by the manufacturing process, which enhances our intention to overcome the challenges in the fabrication of such customized components with complex geometries.

In this paper, we utilized topology optimization as a form-finding strategy to design a shelf for the exhibition of 3D printed ceramic artifacts. The optimization was executed in Millipede [6], a plugin for Grasshopper. We designed a boundary region for 2D optimization with a dimension of 2368mm (L) X 576mm (H) to fit in the exhibition space. Subsequently, according to the result of principal stress lines (white color in Figure 1a), we drew the boundary of the front view to form the geometry and gave it a shelf depth of 200mm. Consequently, the design of shelf represented a multi-hole geometry based on 2D topology optimization as shown in Figure 1b.

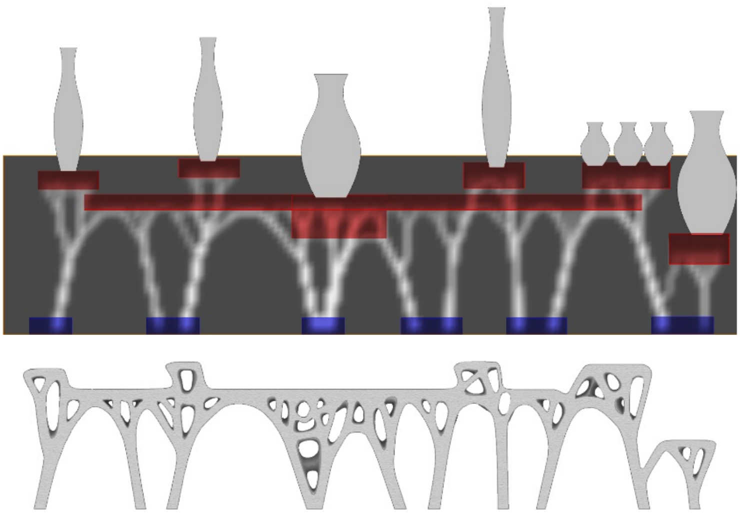

Figure 1. Topology Optimization of the shelf. Top: Dark grey is the optimization boundary, Blocks in red represent the load and ones in blue are the support. Bottom: Finalized geometry based on the principal stress lines with a dimension of 2213mm (L) X 474mm (H) X 200mm (D) and a volume of 64.80 liters.

3. Fabrication

In this section, we will introduce the fabrication of the prototype. It is initiated with a brief introduction of the experiment setup. This is followed by the fabrication procedures: 1. Fabrication of clay mould segments; 2. Assembly and reinforcing clay moulds; 3. Concrete casting.

3.1. Experiment setup

We utilized a KUKA KR 90 R3100 robot arm to control the motion of material deposition (Figure 2, left), with a bespoke end effector. Regarding the extruded clay which represents the outline of the wall and the geometries of cavities for plants to grow must have sufficient stiffness to maintain the shape when sustaining concrete casting, we considered two main factors of the clay extrusion mechanism: the necessary torque to extrude rather viscous material and the precise material deposition rate. In this scenario, we opted the ram pump mechanism to execute a constant clay extrusion (Figure 2, right). This extrusion system consisted of a NEMA 34 stepper motor, a 1: 40-reduction gearbox with cylinder, piston with frames.

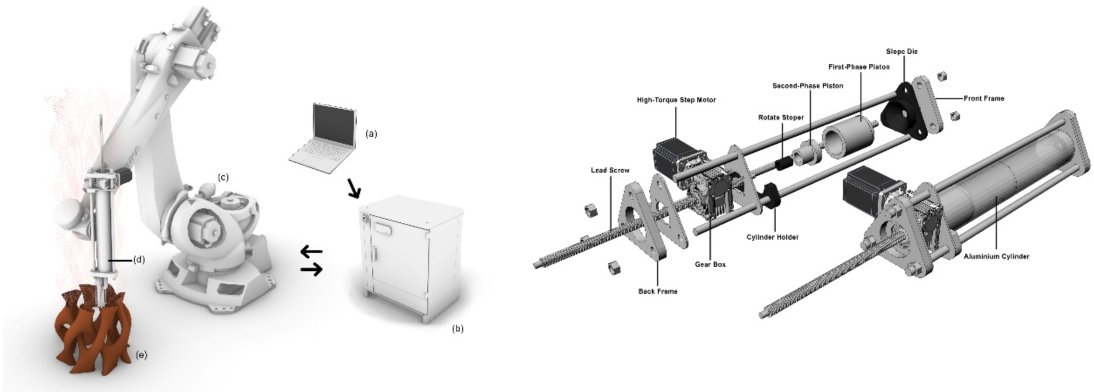

Figure 2. Workcell Setup. Left: Diagram of Setup, (a) Personal computer, (b) Robotic arm controller, (c) Robotic arm as positioning apparatus, (d) Extrusion system and end effector, (e) Printed clay mould. Right: Assembly of clay pump.

The printing material remained the same from the authors' previously research: terracotta clay with 35-40% water ratio through extrusion. We first calibrated the clay AM system to match the extrusion velocity with the nozzle movement speed that facilitated a constant filament deposition. In the case of our pump, each round per minute (rpm) of the motor rotation could extrude 1/90 ml of clay. In this case, to match up a 100 mm/s nozzle movement speed, we set the rpm as 72 for 8 mm nozzle diameter with the printing layer height of 1mm.

3.2. Clay AM extrusion

Considering the overall size and weight of the shelf prototype, we decided to split the fabrication into 4 segments as demonstrated in Figure 3, due to limited manpower. Although this was contradictory to the result of structural optimization, it remained the strategy to investigate our main objective, to improve the fabrication process in terms of the efficiency.

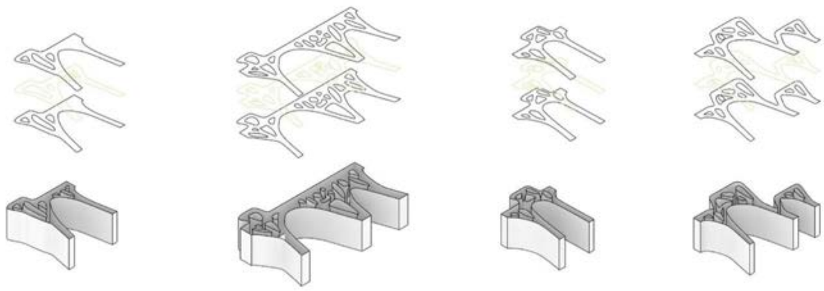

Figure 3. Segmentations of the topology optimized shelf.

Once these geometric models were generated, we subsequently converted them to mesh triangulations for mainly interoperability and precomputation of discretization. The machine paths for our printing setup were produced by contouring the geometry. Our approach here was to translate the machine paths for direct drive of the robotic system. Additional work is required for one to one mapping between the digital and physical artifact within tolerance. Such processes involving computation were executed in the visual programming environment of Rhinoceros / Grasshopper which produces geometric representations of machine paths and converted to robot code using Taco software add-on.

When it came to physical printing, we considered three deficiencies when printing each segment within one process: 1. To fabricate such topological complex objective, the nozzle had to travel inefficiently between prints as red lines in Figure 4, 2. The start and end of each extrusion could cause deformation on the deposited artifact, especially those holes with small cross-section areas, and 3. To switch the extrusion motor on / off caused a postponement for acceleration. In this scenario, we decided to print the interior holes and the boundary envelop of each segment respectively other than print them together as a whole. In addition, for each printing, we transferred the original contoured printing path which was a series of closed curves into one spiral curve to implement a smooth nozzle movement.

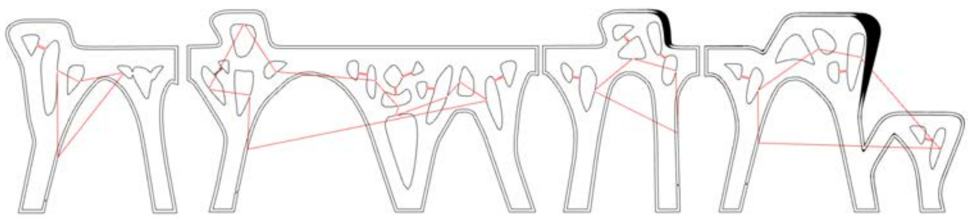

Figure 4. The top view of the printing path for each segment. The black represents the paths where it distributes clay and the red is the nozzle movement without extrusion. In this print job, the wasted nozzle moving distance might increase 15.6% of printing time (5984.6m of extrusion length and 935.1m of free nozzle traveling) exclude the time wastage on motor acceleration.

Besides the concept of printing mould components separately, we also practiced the topological variation in height of each hole as rendered in Figure 5, left. The total printing time to produce every mould components was 16 hours and 38 minutes. This excluded the reprinting of 3 failures out of 33 components representing the interior topological holes.

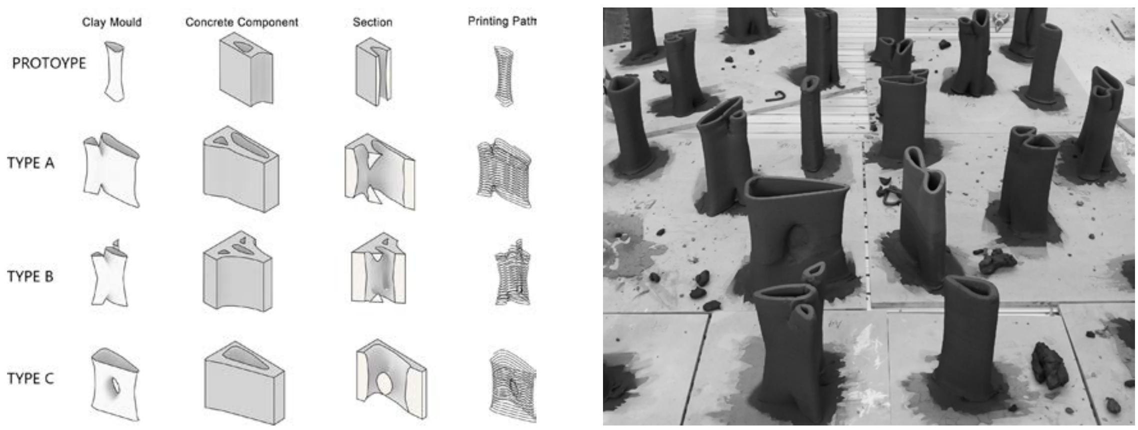

Figure 5. Variations in the topologies of holes. On the left, we present four types of topologies with the geometries of the moulds, concrete components after casting with sections and the printing paths. On the right is a portion of printed works.

3.3. Concrete casting

After the printing of mould components and their post processes, we proceeded to the concrete casting. Our intention was to maintain the humidity of clay mould till concrete casting to avoid the potential surface crack due to dried clay mould absorbing water from concrete, according to Wang et al. [7]. However, the humid clay mould brought another challenge that the deformation of mould would occur during casting due to the pressure exerted by concrete. In this circumstance, the printing of clay mould had to reach a sufficient thickness to sustain the concrete pressure. Nevertheless, it came along with the trade-off between less deformation, a thicker mould as more material to be distributed in a longer time, and shorter printing time.

To response, we proposed the sandbox support as a reinforcement for the clay moulds in Figure 6. Firstly, we placed each piece of interior mould that represented a topological hole into the envelop mould. Subsequently, we surrounded the clay mould with a box made of middle-density fiberboards (MDF) and filled the gap in between with sand. Finally, we cast in concrete with a with the paste of fine aggregates, cement, water and plasticizer (3:2:1:0.005), waited for 24 hours for the concrete curing and demoulded.

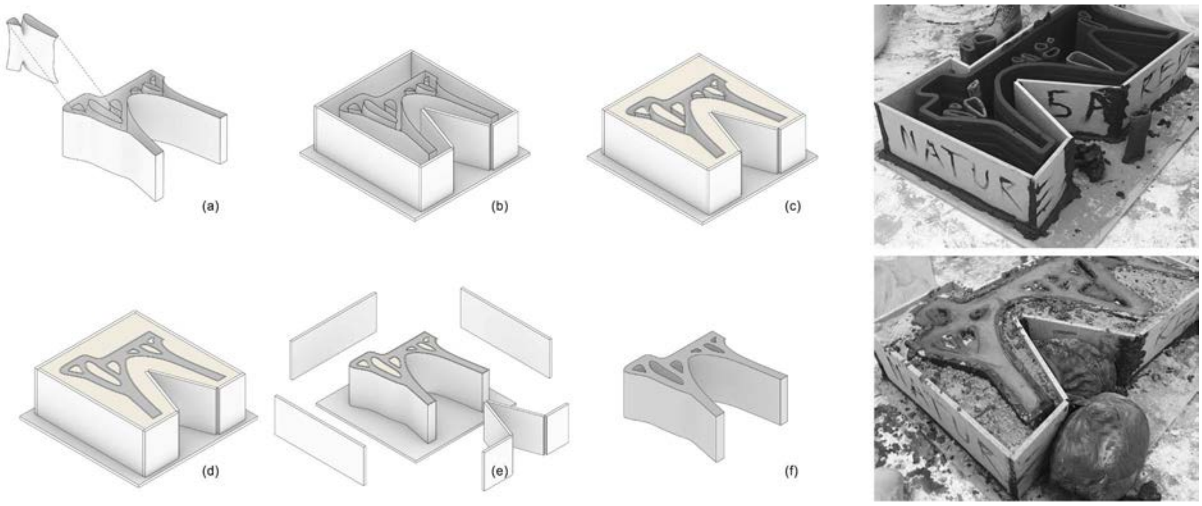

Figure 6. Mould assembly and concrete casting. Left: (a) Assembling 3D printed clay components into the mould for monolithic casting, (b) Surrounding the mould with MDF, (c) Filling the gap between clay and MDF with sand, (d) Casting concrete, (e) Removing sandbox support, (f) Demoulding clay. Photos on the right are fabrication in progress.

4. Result and discussion

We put the fabricated shelf components side by side as presented in Figure 7. There were 64.80 liters of the concrete cast and 47.88 liters of clay distributed as mould that more than 95% was recycled.

Figure 7. Completed shelf.

Through the fabrication process, we detected three flaws as demonstrated in Figure 8: 1. The minimum width of the branch was set as 12mm which resulted in a crack after casting, 2. The sand as support was not condensed that caused the deformation on the longest side of the shelf, and 3. When printing with a sinuous path in a small area, the redundancy of material distribution might cause a displacement.

Figure 8. Flaws in fabrication. From the left: cracks, deformation of concrete casting and displacement in printing.

In response to these, we propose investigating the concrete paste to satisfy the demand for the casting of ultra-thin components. The infilling process of sandbox support has to be secured that the sand is dense and the boundary box is stiff. As for the displacement in printing, we hypothesize that by reducing the extrusion velocity while maintaining the nozzle movement speed, less material will be distributed that retards the redundancy. These hypotheses may be verified in our further research.

5. Conclusions and further development

We presented part of the development for a digital fabrication technology aiming to achieve the topological complexities of concrete artifacts. We highlighted our approach to shorten the total fabrication time which mainly takes place in the additive manufacturing process by mould segmentation and building sandbox support. However, such an approach comes along with trade-offs. Firstly, the mould segmentation is limited by geometry, which means it can not be applied as a general solution to all cases. Although sandbox support seeks a balance between machine fabrication and manpower regarding efficiency, it violates the concept of automation in digital fabrication. Lastly, sand as support ruins the elegance of 3D printed clay mould that it causes trouble in clay recycling since they mix together.

In architecture, the development of software for Computer Aided Design keeps pushing the boundary of design aesthetics and structural efficiency. The demand for materializing these design work has become an ultimate objective that involves researches on novel material and fabrication techniques. We research on concrete since it is one of the most used materials in construction representing workability and durability. When utilizing AM clay mould, we further overcome the difficulties in shaping concrete and the wastage of customized mould. In this scenario, our research will retain the testing of clay extrusion under various printing configurations which aims to understand the behaviors of clay printing in terms of shaping and mechanical performance. Besides, concrete casting will be practiced based on the result of clay AM to determine the successful casting strategies according to deflection and surface finish.

To conclude, we demonstrated positive steps towards fabricating large-scale concrete artifact via additive manufacturing clay mould. There remains a lot more to be investigated to access a better understanding of the material behavior, thus, leading to the control of the fabrication process. We believe such researches will implement the manufacture of concrete components with intricate geometries towards lower costs and potentially higher efficiency.

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