Cocoon: 3D Printed Clay Formwork for Concrete Casting

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1 The resultant cast of 3D-printed clay formwork: the horizontal seams register the pour height from the incremental process; the vertical seams display the location of 'Void' and 'Rib' support structure

ABSTRACT

Concrete, a material widely used in the construction industry today for its low cost and considerable strength as a composite building material, allows designers to work with nearly any form imaginable if the technology to build the formwork is possible. By combining two historic and widely used materials, clay and concrete, our proposed novel process, *Cocoon* integrates robotic clay three-dimensional (3D) printing as the primary formwork and incrementally casting concrete into this formwork to fabricate nonstandard concrete elements. The incremental casting and printing process anchors the concrete and clay together, creating a symbiotic and harmonious relationship. The concrete's fluidity takes shape from the 3D printed clay formwork, allowing the clay to gain structure from the concrete as it cures. As the clay loses moisture, the formwork begins to shrink, crack, and reveal the concrete below. This self-demolding process produces easily removable formwork that can then be recycled by adding water to rehydrate the clay creating a nearly zero-waste formwork. This technique outlines multiple novel design features for complex concrete structures, including extended height limit, integrated void space design, tolerable overhang, and practical solutions for clay deformation caused by the physical stress during the casting process. The novelty of the process created by 3D printing clay formwork using an industrial robotic arm allows for rapid and scalable production of nearly zero-waste customizable formwork. More significant research implications can impact the construction industry, integrating more sustainable ways to build, enabled by digital fabrication technologies.

INTRODUCTION

Cocoon focuses on the creation of concrete elements using 3D printed clay formwork [Figure 1]. Typically, formwork involved in creating complex geometry requires extensive machining time and post-finishing, a material- and labor-intensive process (Kudless et al. 2020). Recent research advancements in concrete fabrication have incorporated 3D printing technologies to create parametrically designed concrete columns with little formwork. Materials seen as suitable for 3D printing shelled formwork include Polylactic Acid (PLA), Polyvinyl Alcohol (PVA), wax, and clay (Burger et al. 2020). This research seeks to advance manufacturing processes of 3D printed formwork by incorporating clay as a viable material for fabrication. The process allows for creating complex geometries that are challenging, if not impossible, with other methods [Figure 2]. Demolding these complex geometries requires little labor, and the demolded formwork can be easily recycled, strengthening its viability as a sustainable construction process.

Reinforced concrete is a fundamental building material that has dominated the construction industry, making it the second most consumed material on earth, contributing to 8% of global human-made carbon emissions (Lehne and Preston 2018). Concrete's ability to take on any form imaginable pushes innovation of the formwork. The formwork used to create complex geometries is incredibly wasteful (Kudless et al. 2020). Methods for producing these complex shapes use technologies, such as hotwire cutting Expanded Polystyrene (EPS) foam, which are toxic and wasteful in their creation (Zhang et al. 2012). While these environmental effects are widely known, reducing its use proves difficult.

Today, designers have challenged this notion of what is possible in concrete fabrication with digital technologies, allowing the creation of formwork for complex geometries. Common approaches to this issue of freedom of shape resort to subtractive methods like Computer Numerical Control (CNC) milling (Gardiner 2017). These methods are both time-intensive and materially wasteful. Additive manufacturing allows for increased freedom of form while reducing material waste in the formwork manufacturing process. Specifically, the development of 3D printing technologies allowed the creation of forms in a nearly zero-waste process. Large-scale Fused Deposition Modeling (FDM) printing technology is continuously advancing, creating a process that can be applied to architecture by integrating industrial robotic arms (Hack and Lauer 2014). The progression of 3D printing technologies gives freedom of form to designers not previously executable at this printing scale. Not only is it thought of as a process for printing building-scale components, but as the formwork for casting these components with traditional cementitious building materials such as concrete (Burger et al. 2020). Combining a high-tech process of 3D printing and low-tech materials such as clay and concrete would potentially enable pragmatic innovation within the construction industry to emerge.

2 The resultant casts of 3D printed clay formwork, stacked, create a geometrically complex concrete column 2m in height

This research seeks to explore the hypothesized benefits of using clay as formwork. We see clay to have several potential advantages, most notably its sustainable nature. Clay is a low-tech and natural material, with its use dating back to prehistoric times, making it one of the oldest building

3 Sequential images showcase clay formwork, self-demolding dried clay and resultant cast.

materials on earth (Gillott 1962). It is commonly understood that clay gains its plasticity when wet and becomes hard and brittle when dry. Due to the shrinkage of the clay as it dries, can the clay begin to self-demold, creating a fast and easy demolding process (Figure 3)? Can the clay then be recycled by adding water to rehydrate and create a zero-waste process? The plasticity of the clay allows it to be extruded for 3D printing of the material in a continuous bead, similar to the traditional process of clay coil pots (Gürsoy 2018). If the clay is easily removable once dried, branching or merging structures could be created using the 3D printing process while maintaining a continuous print bead. To mitigate deformation while casting nonlinear geometries, which increases the irregular hydrostatic pressure, additional support must be generated. Can this process address the building scale and accommodate for geometries not previously feasible to be printed with clay due to geometry limitations such as overhangs and scale?

STATE OF THE ART

Extensive research has been conducted on the topics of concrete, clay, and 3D printing. This section overviews the most relevant research, examining the potential of such processes related to the previously stated research questions.

"Concrete Choreography" (Anton et al. 2020) has explored concrete 3D printing, which utilizes a large bead, reducing the time required to erect the structure. The research involves the development of a fast-settling concrete mix that enables the prints to achieve significant element heights. While aesthetics are explored through the articulation of surface and form, the process integrates internal functional features such as space for reinforcement, alignment details, lighting channels, and rainwater drainage. Compared to using subtractive manufacturing, which cannot integrate the interior functionalities, concrete 3D printing is a nearly zero-waste process and efficient in time from design to completion. Concrete printing allows for geometric freedom without the formwork but comes with issues such as structural layer adhesion (Zareiyan and Khoshnevis 2017). The extrusion process requires aggregates for the mix, which is more carbon-intensive when compared to coarse aggregates of concrete used in traditional cast construction (Xiao et al. 2018). The forms are limited in their overhang geometry as the process does not allow for structural support of the concrete while printing, which traditional FDM polymer printing can accommodate (Burger et al. 2020).

Alternative 3D printing techniques have been explored to create complex geometries with concrete while reducing formwork waste. As polymer 3D printing advances to larger scales, it becomes a viable method for 3D printing formwork for concrete casting. Eggshell, a novel process, explores the challenges of 3D printing thin shell formworks (Burger et al. 2020). Because of the thinness of the formwork, demolding can be done with a heat gun, peeling away the plastic as it melts. While the process creates minimal waste, the plastic may not be suitable for reuse or recycling due to contamination from the concrete particles. If the plastic can be recycled, a labor-intensive process to remove concrete particles that remain on plastic formwork might be necessary. While polymer FDM printing begins to tackle issues of formwork waste and efficiency of complex forms, we ask: can clay 3D printing create a process that is easy to demold due to the fragility and shrinkage of the dried clay, as well as nearly a zero-waste formwork due to the reusability of clay? The increased bead size of clay is comparable to that of other concrete 3D printing processes, which would allow faster printing speeds as the clay does not have to cure while printing.

"Clay Robotics" explores the use of clay as formwork for concrete casting (Wang et al. 2016). The research examines the potential for using clay as formwork and addresses some of the challenges involved in the process. The process explored in this study is sequential, allowing the clay to dry before casting into the mold. A key area of exploration of this process was determining the precise dryness level of the clay to begin casting. It was found that the clay could not be cast into a bone-dry state as it absorbs the water from the concrete, weakening its strength. Limitations to the print height were also observed as the print structurally fails after a certain height and with changes in geometry. Print length is limited due to the size of the tube that can be used for extrusion, creating a discontinuous process. A concrete column results, printing five separate sections, stacking these together, and sequentially casting the column in one pour. This research lays the foundation for further investigations of this process, noting difficulties found such as print height and deformation of the clay due to the hydrostatic pressure and hoop stress. Future work looks to create a more continuous process for printing and casting.

Cocoon builds on advancements in materials and technology. It develops an incremental 3D printing and casting process that works with the limitations of the clay and concrete, allowing the materials to work in conjunction with one another to offset the challenges innate with each material. This process overcomes limitations of scale previously associated with clay 3D printing.

METHODS

Cocoon's novel fabrication process aims to reduce the environmental impact of complex concrete formwork. The introduction of incremental casting and development of a fast-setting concrete mix allows the clay formwork to reach scales previously unachievable (Figure 4). Issues of hydrostatic pressure must be addressed, requiring a continuous casting process using accelerators to give strength to the concrete as it rapidly cures, thus providing stability for the formwork. The process requires the concrete and print to work together to allow for the scalability of the process. Neither the concrete nor the thin shell print would be able to self-support without the other. The devised fabrication method combines the high-resolution material articulation of 3D-printed concrete with advanced concrete casting developed through Smart Dynamic Casting (SDC, Lloret-Fritschi et al. 2018). By printing the clay formwork instead of 3D printing the concrete form itself, *Cocoon*'s process allows for intricate detail, undercuts, and void generation, creating a wider range of geometries achievable.

This novel process requires the investigation and fulfillment of several key interrelated research objectives: a suitable fabrication setup, material formulation of a fast-hardening concrete ideal for working with clay formwork, development of a custom computational toolpath generator, a sequential clay 3D printing, incremental concrete casting process, and a demolding process. To investigate the objectives discussed above, this research focuses on physical prototyping, informing the development and refinement of *Cocoon*'s fabrication process, coupled with computational design experiments and simulation studies. Subsequently, the potential for building-scale manufacturing of architectural elements is validated by fabricating a geometrically complex case study component. We will discuss each of these topics in the following sections.

Fabrication Setup

The fabrication setup has been developed at the University of Michigan Taubman College of Architecture and Urban Planning (Figures 5 and 6). The setup comprises a 6-axis industrial robotic arm with a clay extrusion end effector. The extruder requires the clay tube to be refilled after 250m of print, a crucial factor in the development of this process as the print needs to stop and start for a tube change. Mixing and clay filling stations are located adjacent to the print work cell to allow continuous filling and mixing. The orchestration of the printing, mixing, and clay filling create an incremental process that works with the limitations of the current setup.

Initial Experimentation

The research was conducted in several phases, building up to a case study that applies the developed process to an architectural element. The first phase compared the deformation of a cylinder 100mm in diameter and 250mm in height using terracotta clay. Three prints with varying bead heights were extruded and subsequently cast into. Bead heights of 1mm, 2mm, and 3mm were compared, and it was found that the cast with 1mm bead height observed the least amount of deformation. Our test confirms the results of past research (Wang et al. 2019), where the bead height was tested and compared for deformation.

The second phase of the research looked to compare the plasticity of clay types as related to deformation. Clay types with high plasticity were sought after because it was hypothesized its strength would limit deformation in the cast. Two porcelain clays with varying material compositions were selected due to the material's high plasticity and workability. Terracotta, a clay with lower plasticity, was tested against the porcelain clays. An increased print height of 450mm necessitated introducing the incremental casting

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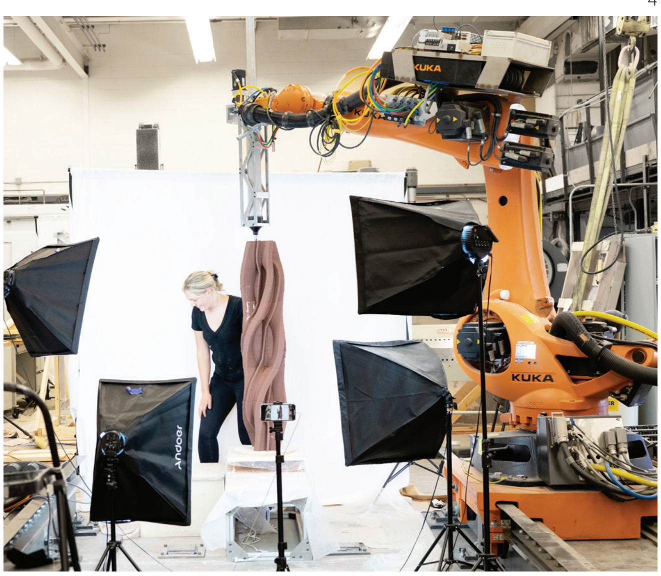

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4 The combination of robotic clay printing and manual concrete casting creates a co-working environment with the human and robot

5 The fabrication setup, including 6-axis robotic workcell with clay extruding end effector

process, which will be discussed in the next section. The experiment resulted in a negligible difference in deformation between the clay types, although further testing is needed to evaluate this more accurately. Also, it was found that the surface finish of the clay varied in each of the casts, with terracotta yielding the cleanest finish, so it was ultimately chosen as the clay to move forward with. The terracotta stains the concrete, exposing a trace of how it is fabricated, creating a connection between the geometry and material articulation of the formwork.

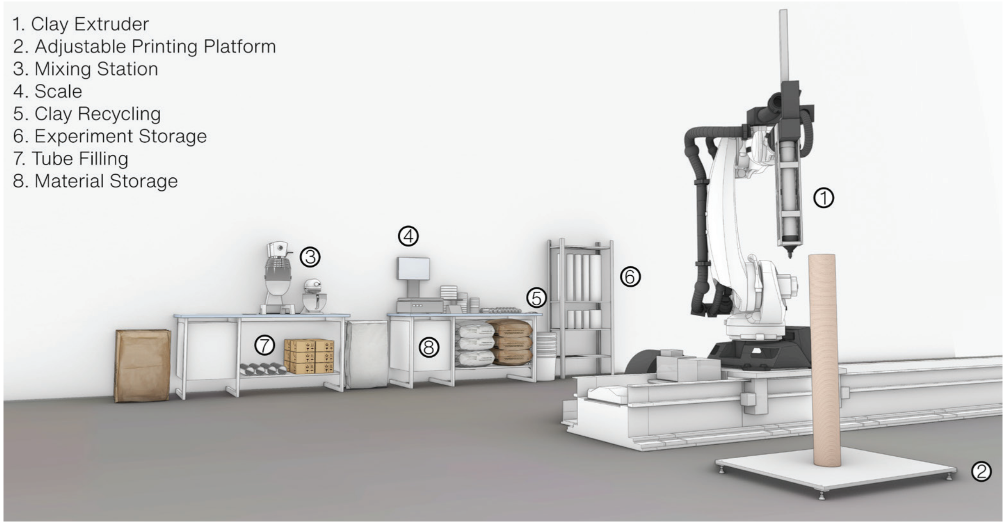
The next phase of the research consists of a rigorous testing process to fine-tune three main factors in deformation control of the clay; print height, concrete mix, and casting timing.

Deformation Control

Incremental casting is a process that learns from SDC, pouring concrete in several increments and allowing the concrete to begin to cure as the next section is poured (Lloret-Fritschi et al. 2018). This control of the curing process is done using an accelerator in the concrete mix. The accelerator amount, the pour height, and timing between sections become a balance of factors explored in this phase of the research. The goal of the incremental casting is to allow for two sections of the print to bond while not affecting the earlier sections. More specifically, the first section will be cast, then a second a specified time after (for instance, 20 minutes). These sections will bond as the concrete has only partially cured. The third section of print aims to bond with the second section while not affecting the first, to control the hydrostatic pressure of the concrete, thus limiting deformation.

The primary driver in the design of concrete formwork is the control of hydrostatic pressure. Limiting the pour height controls the amount of hydrostatic pressure and therefore, decreases the deformation in the final cast. Concrete with the same density will have the same pressure on the formwork based on the height, not volume or weight. An additional stress on the formwork result from the hoop stress, which causes further deformation on the circumference of a cylindrical form as the material will elongate in proportion to its length (Roylance 1996). Hydrostatic pressure can be controlled through variations in the print height. For this set of experiments, the cylindrical form is again used for consistency maintaining a diameter of 100mm. Heights of 100mm and 135mm are then used to compare the deformations.

The base concrete formula consists of cement, ground silica, silica fume, water, polymer, superplasticizer, fine



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6 The fabrication setup utilized a 6-axis robotic arm with clay extruding end effector; stations for mixing, tube filling, and clay recycling are supplemental to the cell

sand, and glass fiber reinforcement, creating a Glass Fiber Reinforced Concrete (GFRC) mix. The formula is mixed in small batches using an industrial mixer. Two minutes before casting, an accelerator is added to the GFRC. The use of 1.7% and 2.6% accelerators are compared in this study (Figure 7). The percentages are considered high compared to SDC, which must accommodate tube changing and printing times due to the longer timing between the casts. As mentioned, timing is an essential factor in this process as it relates to the mix and fabrication setup. A minimum of 15 minutes is required between casts to allow the regular tube-changing during the setup.

This phase of tests was conducted by creating cylindrical columns measuring 800mm in height. Combinations of parameters were tested in a rigorous set of experiments to develop a process balancing the timing, mixture, and section height. Limiting the section height to 100mm and accelerator to 1.7% while extending the timing to 20 minutes resulted in minimal deformations while maintaining layer adhesion between the two sections.

The Cocoon

In the final phase of the research, to prove the viability of 3D printed clay formwork for concrete casting, a case study experiment is designed to overcome the challenges of the process. Ease of fabrication, customization, and scalability are considered as the driving factors in the prototype. The minimal surface showcases the potential of the intricate detail, undercuts, and voids, accommodating nonlinear surfaces.

In the first prototype, the concrete casting caused relatively large deformations and resulted in formwork failure due to large overhangs combined with unachievable pour heights. The exterior formwork of this test created a concave vessel. The hydrostatic pressure and futility of the concrete pushed the formwork to failure, proving the need for a more rigid formwork. So, improvements including casting height, minimal surface design, additional scaffolding support, and a thinner wall depth were investigated in our next prototype.

Although the 3D printing cylinder tests enabled informed selection of clay type and fabrication parameters through physical prototype analysis, they did not showcase the achievable geometric complexity. The cylindrical test purpose were to investigate the effects of hydrostatic pressure on the malleable formwork. To prove the viability of the 3D-printed clay formwork, complex form testing was necessary.

By implementing computational design into the fabrication process, a continuous toolpath generator is created using Grasshopper, a visual algorithmic editor integrated into Rhinoceros's 3D modeling tools (McNeel 2020). The custom toolpath generator provides the boundary for concrete and creates a minimal surface supporting branching structures known as 'Void Support' (Figure 8). Moreover, to improve the rigidity of the formwork, an additional support system named 'Rib Support' is added to the clay printing toolpath. Compared to printing two layers around the circumference of the geometry, Rib Support conserves clay and provides additional strength to the formwork only where it is needed, reducing print times (Figure 9). The Rib Support was generated, providing additional support buttresses to points of failure or deformation observed during initial tests. Due to the increased hydrostatic pressure from the complex geometry, pour heights were adjusted from 100mm to 50mm between the casts. Integrating computational toolpath generation demonstrates the potential for optimization of the concrete casting process and clay formwork structure. Furthermore, both the Rib Support and Void Support do not create a break or overlap in the toolpath, which could create a seam vulnerable to failure.

Demolding

After the fabrication, the resulting concrete and clay structure is self-supporting. Over 1-3 days, the clay formwork begins to self-demold. As form loses moisture, the clay starts to shrink, creating fractures within the formwork. This phenomenon is directly linked to the inherent material qualities of the clay and is unique to *Cocoon*'s novel technique. The remaining formwork is then removed with ease with no additional tools (Figure 10). The clay can then be rehydrated, filtered, and recycled internally. This displays the potential of clay formwork to be a viable low-waste option. More testing is necessary to verify the material deterioration of this process.

RESULTS AND DISCUSSION

The initial experiments aimed to incrementally cast concrete forms without failure, while the deformation-controlled experiments aimed to improve the methods and techniques used in fabrication. Using 10 grams of the accelerator, six pours at the height of 135mm per cast created a concrete cylinder reaching a height of 810mm without failure. This test did have visible deformation (Figure 11). With an additional 5 grams, a test was conducted using 15 grams of the accelerator, six pours at the height of 135mm per cast. Although the deformations were significantly reduced, the disadvantage of adding more accelerator was less layer adhesion. In contrast, by lowering the height of each cast, fewer deformations were observed, and layer adhesion was maintained.

A third experiment using 10 grams of the accelerator and eight pours at the height of 100mm per cast created a concrete cylinder reaching a height of 800mm. This experiment was conducted three times to gain data on the replicability of the process. The accuracy of each cast was calculated by incrementally measuring the circumference of each cast. On average, the circumferences of the resulting casts were within a millimeter of accuracy (Figure 12).

The investigation of the cylindrical tests illustrated two main factors in increasing the deformations: first, the increase in the height caused higher hydrostatic pressure; second, the increase in the diameter resulted in higher circumferential hoop stress. This research determined a balance between these tested factors for this specific geometry. Although helping in understanding the limitation of clay formwork, the cylinder deformation testing results are only applicable to this particular geometry.

The results of this experimentation set up a framework for applying this process to different geometries. As seen in the case study experiment, the geometry was tested and adjusted to accommodate a complex form. The successful process of fabricating the case study not only determined Cocoon as a viable process but created an experimental setup that has the potential to be adjusted and applied to many geometries.

The overall height of the resulting case study element was 1.3m. The incremental casting process consists of 13 clay prints with 26 consecutive concrete pours. This process took a total of 9 hours to print and cast for the overall geometry.

CONCLUSIONS

Cocoon investigates the use of 3D-printed clay as formwork for concrete casting that eliminates waste in the process of creating complex forms. The developed incremental casting process allows clay printing to reach a previously not achievable scale by having the concrete work together with its formwork to hold the structure. This novel process reduces the environmental footprint of creating complex concrete forms by minimizing the material waste. The process enables the integration of voids and overhangs due to the ease of removability of the formwork, mitigating constraints of concrete 3D printing. Overall,

Cement	Silica Fume	Ground Silica	Water	Accelerator	Polymer	Super Plasticizer	Sand	Glass Fiber
562.5g	75g	150g	195g	0g	37.5g	7.5g	562.5g	22.5g
562.5g	75g	150g	195g	10g	37.5g	7.5g	562.5g	22.5g
562.5g	75g	150g	195g	15g	37.5g	7.5g	562.5g	22.5g
562.5g	75g	150g	175g	10g	37.5g	7.5g	562.5g	22.5g

7 Concrete mix formulations

Cocoon seeks to challenge conventional methods and materials for 3D-printed formworks, demonstrating the ability to reduce the environmental impacts of concrete construction without compromising the complexity and time efficiency of bespoke architectural elements.

Future Work

The current fabrication setup has projected multiple opportunities for concrete formwork production; however, it is limited in scale due to the tube volume of the clay, requiring frequent tube changes, thus slowing down the process for larger-scale production. The integration of mud printing using a pump, a technology that had been recently developed for large-scale earth printing for architectural assemblies, would allow the process to jump to the production of building-scale architectural elements (Gomaa et al. 2021). For this process to be applicable at that scale, reinforcement must be integrated. We are looking into developing a fabrication setup that situates the print bed between two industrial robotic arms, one equipped with clay printing and the other rod bending. The ability to integrate the robotic rod bending process into the overall process mitigates the structural scale issues. This multi-robotic fabrication cell allows for cooperative coordination of the placement of reinforcement during the incremental printing process. Future work looks to integrate this collaborative process of rod-bending reinforcement and pumping concrete into the formwork using a tool that can mix accelerator into the concrete at the nozzle for the most consistent results.

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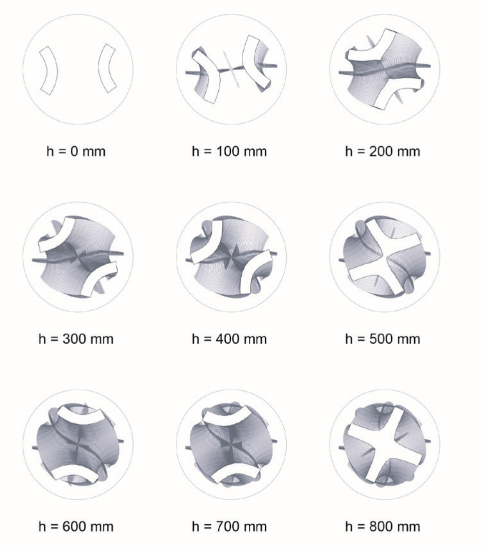

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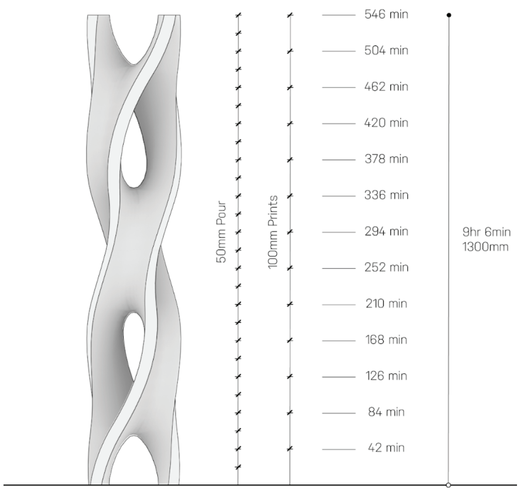

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8 The plan of toolpath generation at alternating concrete pour heights displaying location of the support structure based on geometry

9 Pour heights as they relate to geometry and time. Overall, the 1.3m structure was printed in 9 hours and 6 minutes

10 The final resultant cast after demolding with 1.3m height

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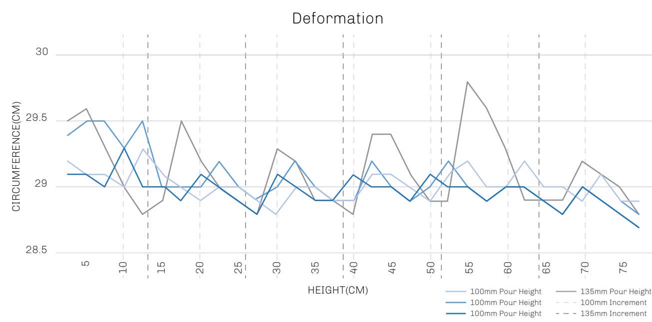

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11 The deformation tests: (From left to right) 100mm pour height 10g acc; 100mm pour height 10g acc; 100mm pour height 15g; 135mm pour height 15g acc; and 135mm pour height 10g acc

12 The deformation relative to pour height for 100mm diameter cylinder

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