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Cast-in-place Freeform Concrete with Big Area Additive Manufacturing Formwork

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Abstract: Parametric design and digital fabrication give precise control in the design and materialization of complex geometric forms. Large-scale additive manufacturing machines can fabricate digitally generated architectural forms quickly and economically at full scale. However, their application in building construction has been limited. Through a case study, this paper examines integrating parametric design with material and constructed reality through 3D printed formwork for cast-in-place concrete. The following details are presented: (1) creating a parametric model capable of designing, testing, and manipulating the customized freeform in response to construction and material constraints, (2) fabrication method of big area additive manufacturing of formwork with carbon fiber reinforced acrylonitrile butadiene styrene plastic, and (3) construction process (studying material behavior, testing the formwork, and the final onsite concrete cast).

Keywords: Parametric design, big area additive manufacturing, cast-in-place concrete, freeform

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1 INTRODUCTION OF 3D PRINTING

Typically, 3D printing produces representational architectural models and not full-scale objects used in building construction. With small scale representational models, there is a lack of focus on the realities of architectural material and tectonics encountered in the world of construction. By contrast, additive manufacturing (AM), a type of 3D printing technology, is commonly used to produce full-scale printed parts for the aerospace, automotive, energy, and marine industries. The emergence of large-scale AM machines is being harnessed to explore new formal complexities as both representational models and for use in building construction (Talbott 2006). Research has been done in material explorations with foam (Chan and Crolla 2019), sand, metal (Aghaei *et al.* 2019), and concrete (Marijnissen *et al.* 2017) using AM, casting, and other digital fabrication processes. However, much of the research has tended to focus on smaller building components such as panels (Bell 2012), joints (Aghaei *et al.* 2019), and space frames (Raspall and Banón 2016).

2 3D PRINTING AND CONCRETE CASTING

3D printing methods related to full-scale concrete structures can generally be grouped into two categories: directly printing with concrete or by printing a mold or formwork. Direct concrete printing can be done off-site with industrial robots to make large modular building components. It can also be used for onsite construction, like with the freeform Mars dwelling prototype by NASA. However, direct concrete printing has not been commonly used in construction due to the difficulty of placing rebar and weak bond strength between printed layers (Mudaliar *et al.* 2020). It also lacks the flexibility to adapt to onsite construction constraints and unpredictable environmental conditions. On the other hand, formwork produced by 3D printing, CNC milling, and robotic wire cutting can be manufactured precisely under a well-controlled factory environment and assembled on-site for concrete casting.

In recent years, the Oak Ridge National Laboratory and the Precast/Restressed Concrete Institute have promoted the development of a large-scale AM machine, big area additive manufacturing (BAAM); its use has been emerging in the architecture, engineering, and construction (AEC) industry (Roschli *et al.* 2018). This piqued discussions on the economic benefit of using 3D printed reusable formwork, which was studied during the cast of many concrete panels (Bell 2014) and in comparing the cost of the plastic mold with wood mold making (Roschli *et al.* 2018). Many hybrid methods such as 3D printed plastic formwork (Jipa and Mathias 2017), adaptable vacuum-forming mold (Swackhamer and Satterfield

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2013), flexible formwork (Engholt and Pigram 2019), and water-soluble formwork (Doyle and Hunt 2019) have also been proposed to reduce the cost of mold making.

Inspired by AM technologies and their potential in the AEC industry, the project team formed by the faculty at the University of Cincinnati, architects at the jose garcia design, and production engineers at the Cincinnati Incorporated researched and experimented with fabrication methods to produce a full-scale freeform concrete. These methods include concrete printing directly and concrete casting with various mold making processes.

3 SMALL-SCALE PROTOTYPES

The research team experimented with a series of small-scale prototypes to investigate the relationship between parametric design and digital fabrication processes. Several freeform panels with a complex pattern and CMU blocks were digitally constructed in Rhino. Scripts in Grasshopper were used to assist in the iterative design process and in generating tool paths for use in production with robotic arms, CNC, and 3D printing methods.

There are three small-scale prototypes the researchers have investigated (Figure 1). The first prototype utilized 3D printing to make a CMU block with Acrylonitrile Butadiene Styrene (ABS) material, which was then cast into a negative silicon mold. The fragile silicon mold was then re-casted into a stronger plaster mold. The reusable plaster mold was used to cast many CMU blocks. The inaccuracy in the cycle of mold making and transitioning from one material into another became an obvious issue. The deformation of the silicon translating to the plaster mold made the final CMU blocks fail to align with each other. Furthermore, the ABS model and the silicon mold are wasted after the casting.

The second prototype utilized durable high-density foam milled by CNC machinery to create a wall panel. The milled, positive foam panel form was used for thermoforming to produce a negative plastic formwork for concrete casting. The thin plastic mold produced by thermoforming can only survive 2-3 concrete pours and tends to warp over time.

The third prototype used the Kuka robotic arm to direct 3D print clay material. The weak bonding strength of the mixture, especially in overhangs, made it easy to collapse during the printing process. These small-scale prototypes helped the design team understand the challenges and limitations of various fabrication methods related to concrete (Figure 1).

4 3D PRINTING WITH BAAM

The design team applied the research of digital fabrication and freeform concrete casting to a full-scale commissioned project, a new residence with several 13 feet tall, customized concrete columns that span an area roughly 75 feet long and 30 feet wide. The freeform design concept included a novel way to distinguish space in an otherwise open concept upper level. Using concrete, which has a heavy look and feel, columns gently morph from support

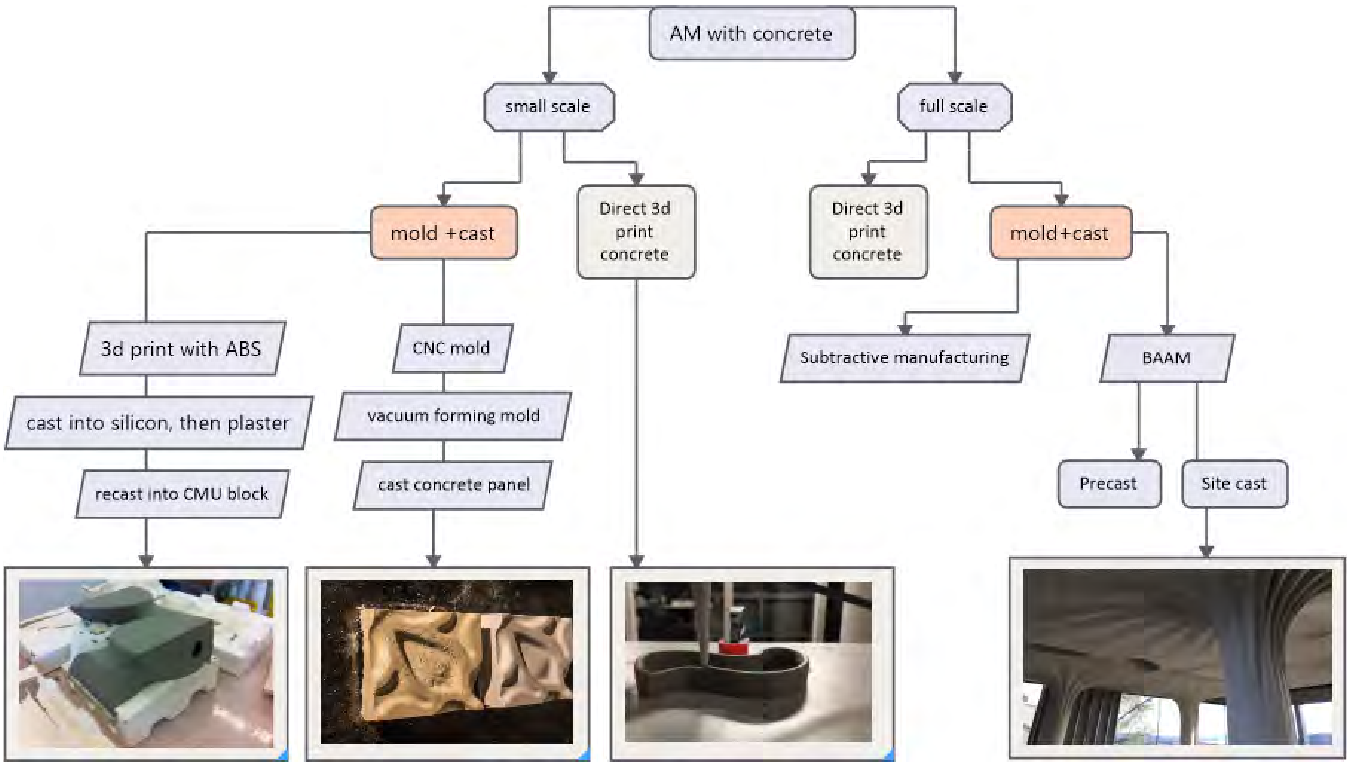

Figure 1. Small-scale prototype with plaster mold, thermoforming mold, direct robotic 3D print (left); full-scale BAAM and site cast-in-place concrete (right)

to ceiling while introducing flutes, giving the appearance of fabric blowing in the wind. This resulted in the defamiliarization of concrete presented in a light and flowing manner.

In the search for a formwork fabrication method that would work at the scale of the columns, two approaches were considered. First, a subtractive manufacturing technique to create the mold used for making the formwork. The second was to use AM to directly print the formwork. Each method was evaluated in terms of production time, precision, material, and labor cost. The cost summary of these methods can be seen in Table 1.

With the subtractive manufacturing approach, the final topology is CNC milled out of high-density foam, assembled, surface sanded, and coated with epoxy and form-release to act as the positive form mold. Then, the mold is sprayed with layers of fiberglass to create the final formwork. CNC milling the foam has the quickness and precise tolerances of digital fabrication, but the fiberglass spraying stage requires processes by hand that are not as quick or precise. Manually segmenting the fiberglass formwork into pieces and crafting the attachment flanges for complex geometries can cause tolerance and alignment issues during onsite assembly. The thickness of the final sprayed fiberglass shell may be thinner in places, which can cause potential blowouts during concrete casting. Compound all these issues with the significant addition in labor costs for a less precise, manual processes of the fiberglass stage. Additionally, degradation of the form of positive mold and fiberglass negative formwork during post-cast pulls require repair or reproduction work, adding material and labor costs. In the end, there would be roughly 165 cubic feet of discarded foam material per column using this method.

Contrast this with the AM approach wherein the formwork is printed directly, not relying on waste material and added labor to yield the final shape. Using AM to print the large-scale column formwork required the use of BAAM, an industrial-sized 3D printing machine. BAAM uses thermoplastic pellets to extrude print material at 80 pounds per hour. The machine offers several plastic print media to choose from: ABS, PPS, PC, PLA, and PEI with the possibility to add carbon, glass, or organic fibers to improve strength and thermal stability. Slicing software allows precise division of the print piece as needed and calculates tool paths, which results in machine precision for the entire printed formwork. Printed pieces can then be post-machined to a smooth surface if required. The strength and integrity of the printed formwork pieces using the BAAM give the ability for increased casting pulls beyond what is possible with the subtracting manufacturing approach. The speed, precision, lack of reliance on wasted material, and reduction in added labor made BAAM the more desirable method.

4.1 Parametric Workflow

The computation team was able to digitally construct the column structure controlled by a set of parameters, which was shared with the design team through a Grasshopper script. Driven by these parameters, a double-curved, parametrically derived column was able to be customized by the design team using a simplified user interface containing several control points, siders, and buttons. It was an iterative process to find the right balance of visual aesthetics, response to material behavior, construction requirements, and adjustments for concrete casting difficulties learned from prototypes (Figure 2).

The radial-patterned fluting became the aesthetic focus of the design. Each flute contains several control points to define its curvature and has intricate, complex characteristics in its lofted surface to form a continuous ceiling. Its convex and concave pattern moves across the neighboring column form and provides a seamless ripple across the entire space. The parametric model gave the design team full control of the 3D pattern across the surface by densifying and scaling formal elements on its surface through manipulating control points and input values.

Linking the parametric model of the column and ceiling surface into the building information model (BIM) of the residence allowed the design team to evaluate the design in context through 3D rendering while also detecting

Table 1. Cost differences between CNC milling vs. directly printing the formwork with BAAM

Cost differences between CNC milling vs. directly printing the formwork with BAA for one column		
	Foam CNC Milling + Fiberglass Shell	BAAM
	Positive Mold Production	
Material Cost	$20,000.00	n/a
Labor Cost	$15,000.00	n/a
	Casting Formwork Production	
Material Cost	$22,000.00	$42,500.00
Labor Cost	$33,000.00	n/a
Total Cost	$90,000.00	$42,500.00

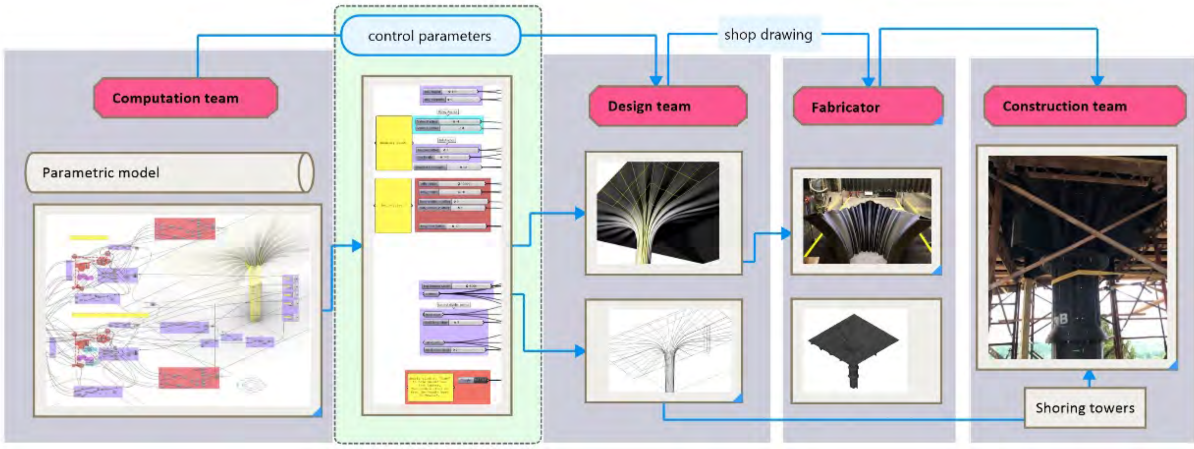

Figure 2. Grasshopper script to support the customizable parametric freeform

collisions with, and insufficient clearances from, building structure and rebar reinforcement. The Grasshopper script allowed the design team to adjust the freeform model in real-time to continuously evaluate both the aesthetic design and necessities of construction using the digital 3D surface and automatically generated 2D section cuts, creating an iterative feedback loop. After realizing the freedom modeling allowed, the design team focused on the translation of the parametric model into a shop drawing for the fabrication team to produce the concrete casting formwork.

4.2 Fabrication Process: Column Formwork with BAAM

The design team studied the formworks required performance, printability using BAAM, and constructability. This review led to the decisions regarding print material, thickening of print walls, strategically dividing the formwork into pieces, and adding support and connection flanges. The parametric model was able to be transferred to the fabrication team to serve in their production of shop drawings.

For the fabrication of the formwork, carbon fiber reinforced acrylonitrile butadiene styrene (CF ABS) was chosen for its added strength and dimensional stability. During the printing process, the fibers keep the piece from warping as it cools. In addition, CF ABS strength can hold the load of the curing concrete and the construction team during the casting process. BAAM requires that each 0.34″ wide print bead layer begin and end in the same position. The nature of printing an outer shell to use as formwork meant the print path would double back adjacent to itself, leading to a 0.68″ thick double bead print wall being implemented; this also has the added benefit of redundant strength as a factor of safety to contain the thrust and dead weight from the poured concrete.

The print bed on the BAAM 806 machine allows producing pieces up to 240″ long, 90″ wide, and 72″ tall. With the vast size of the columns, careful consideration was required in the division of the overall formwork into parts sized to fit within print bed limitations (Figure 3). The vertical angle threshold for BAAM is 45 degrees from the vertical axis, and, with the nature of the column shape, the print orientation of the pieces needed to change as the surface transformed from vertical to horizontal due to questions of stability while printing. A consequence of the print orientation change was the discontinuity of print grain direction from piece to piece. The overall strength would not be affected, and the aesthetic implication of the different grain direction was deemed unimportant.

Joints with flanges were added to create a level datum to be supported on shoring towers and to facilitate the bolted assembly of the 98 individual formwork pieces. The freeform column geometry lacking sharp edges along with aesthetic, cost, and scheduling reasons led the design team to forgo post-machining the printed formwork. The AM process then became visually apparent in the final product as each new 0.15″ height layer of CF ABS is expressed in the formwork, developing emergent material behavior from manufacturing processes and material composition.

4.3 Site Casting

4.3.1 Early casting test

The purpose of the test concrete casting was to observe the material properties of the chosen concrete mix and its structural behavior. The final column design was cast around structural steel wide flange columns of the building structure and contained shrinkage steel rebar within a close distance; combining these tight clearances with the fluted shape meant the concrete mix had to flow past the obstructions with ease due to the inability to access lower portions of the column with vibration equipment. Thus, several modifications were implemented in the concrete: First, the mix replaces 75% of the Portland cement with slag to create a lighter color. Next, a plasticizer was added, and modified aggregate was used to make a self-consolidating mix with a high spread (29″

on spread testing) that promotes better flow through the tight clearances and adequately fills the flutes without needing labor-intensive vibration. Finally, a shrinkage reducer was introduced to prevent surface cracking and preserve the surface imprint from the AM process used to create the formwork.

During the test cast, a portion of the final formwork was used for the modified concrete mix to study the flow, distribution, and lateral pressure of the concrete on its formwork. A series of bolts were installed through the connection flanges to make a rigid mold. Pieri Eurowax form release was chosen because of its ease of application and retention in the AM print grain, allowing repeated form pulls without labor-intensive cleaning and destruction to the formwork or the concrete surface. After the concrete cured, the formwork was disassembled for future reuse. Observation of the test casting confirmed that the concrete additives and form release created the desired result: a high-spread, fluid mix that captured the fluted formwork completely down to the AM grain. The formwork strength held the fluid pressure of the cast and was able to be removed non-destructively (Figure 4).

4.3.2 Cast-in-place concrete on-site

Installation of steel rebar reinforcement was the first step in preparation for the on-site cast. The digital model was used to create fabrication drawings of the rebar cage in the column. The cage was welded in the shop and installed on-site (Figure 5). The upper reinforcing steel mat was placed once the formwork was assembled. With the steel cages installed, concrete shoring towers were assembled for support during the first concrete cast. The 98 individual pieces were craned into place atop the shoring and bolted together to create a complete formwork for three out of the six total columns (Figure 5). With the first complete formwork in place, rebar reinforcement

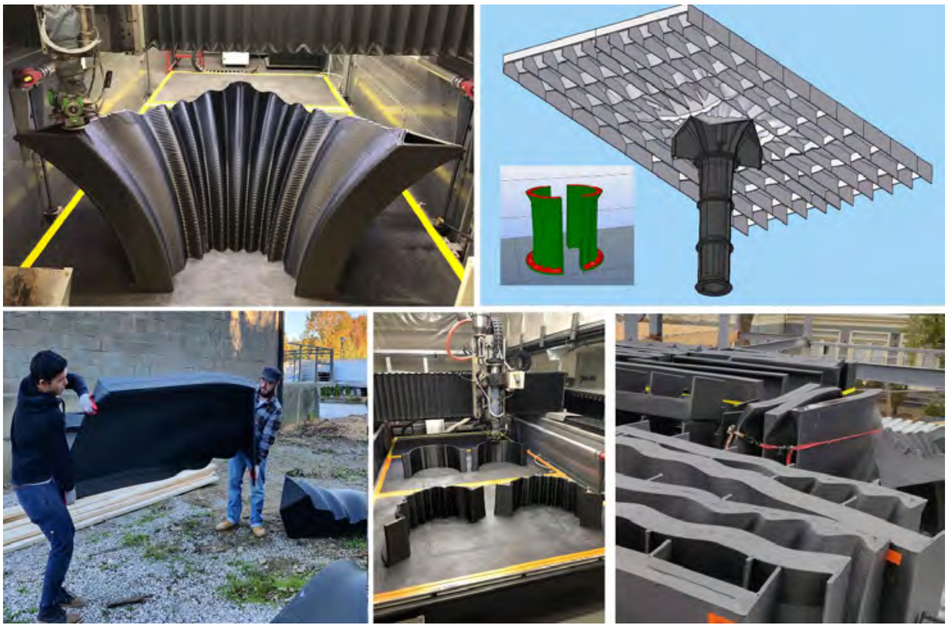

Figure 3. CF ABS 3D printed formwork with BAAM at Cincinnati Inc (image and photo provided by Cincinnati Inc. and Jose Garcia Construction)

Figure 4. Test cast using 3D printed formwork (photo provided by Jose Garcia Construction)

Figure 5. Field installation of shop fabricated steel reinforcement for the columns (photo provided by Jose Garcia Construction)

Figure 6. Self-consolidation concrete mix pumped into the formwork, flowing around steel rebar and into concrete formwork fluting (photo provided by Jose Garcia Construction)

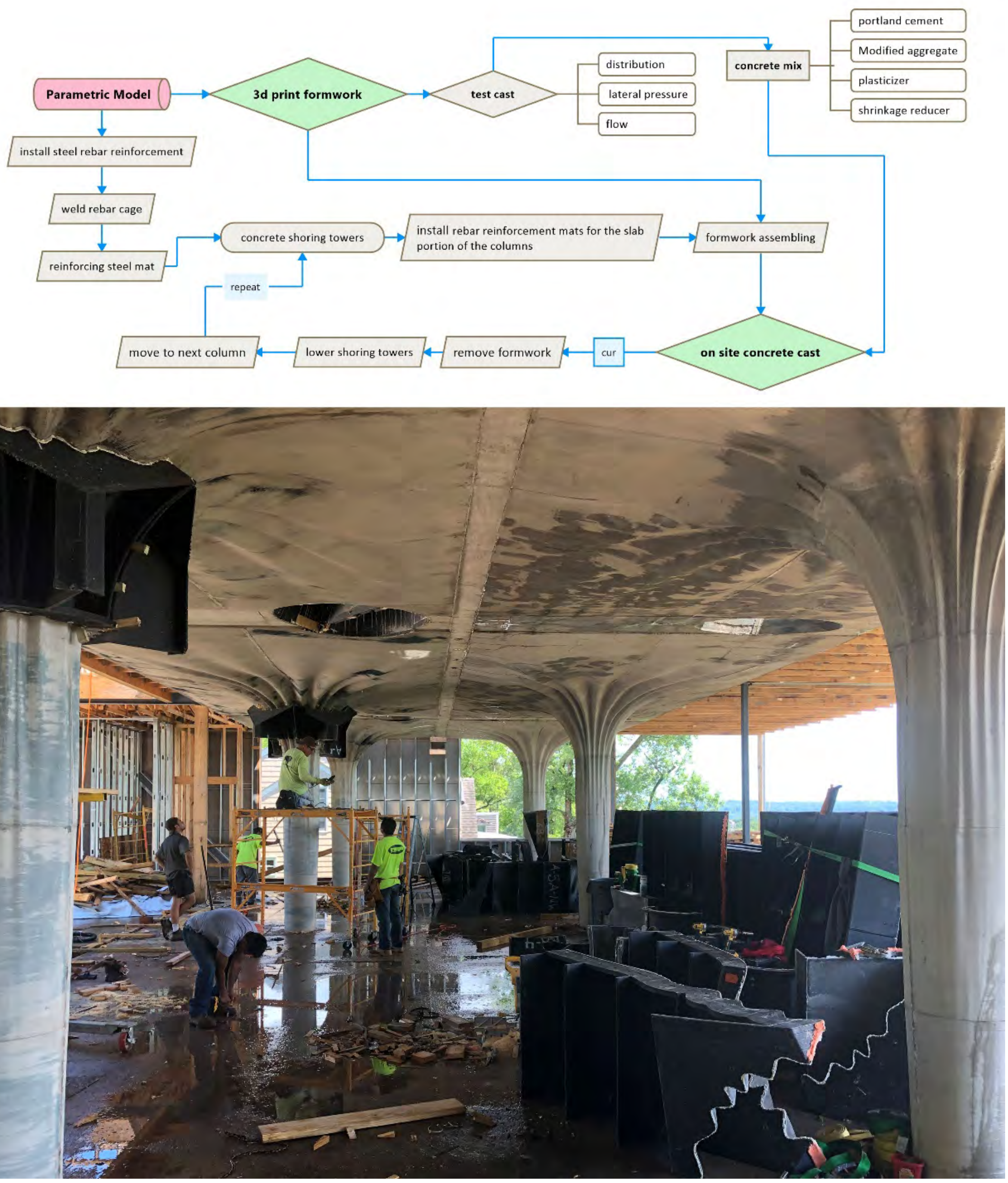

Figure 7. Shoring tower erection, removal, and re-bolting the reusable formwork assembly, part of the repeated workflow (photo provided by Jose Garcia Construction)

mats for the slab portion of the columns were installed and stubbed through a pour stop that would act as the central seam joining the two casts. During the assembly process of the first set of three columns, it was decided to include concrete skylight wells that would puncture the ceiling slab. The BAAM process allowed a quick turnaround from design to fabrication to installation in time for the first onsite casting. With the skylight formwork installed, concrete was pumped in from atop the formwork carefully, ensuring the proper filling of the formwork (Figure 6). After the first cast had been cured, the process began for the second casting. Shoring towers were lowered and slid to the second row of three columns. Formwork pieces were then carefully removed and slid on a mobile track to their corresponding position for the second casting. The formwork was re-bolted together, rebar mats were installed, and concrete was poured to complete the entire process (Figures 7 and 8).

5 CONCLUSIONS

This learning-by-design project explored the convergence of parametric modeling, AM, cast-in-place concrete, and their impact on the project budget and project delivery schedule. BAAM can significantly reduce production time by providing a rapid fabrication process. The fast-printing speed can be optimized further by removing the post-machining and smoothing process. Further, direct formwork printing does not rely on wasted material for use as a positive form mold and offers greater stability

Figure 8. Completed work of cast-in-place concrete; visible bead lines from the BAAM were transferred into the concrete (photo by Ming Tang)

for reuse. Overall, BAAM yielded a lower cost for formwork production.

In the traditional AM process, the digital form making approach can become highly abstracted. It usually puts the architects in a position where a material study and tectonic solutions take place after the design process, leaving many of the considerations to the fabricator and construction team. With this full-scale column project imprinted by the processes that created it, the design team was able to use the parametric model to take into direct consideration material behavior, construction constraints, and production of shop drawings for the column formwork. The authors believe the disconnection between architects, fabricators, and contractors can be bridged by data sharing through parametric modeling and supported by BAAM technology to yield an economic and digitally assisted tectonic process. The customizable freeform design, formwork fabrication, and site cast-in-place concrete elucidated the relationships between matter, form, and processes.

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