3D PRINTING OF MOLDS AND OTHER INNOVATIONS TO REDUCE CONSTRUCTION TIME ON A LARGE, HIGH PROFILE ARCHITECTURAL PRECAST PROJECT AT THE DOMINO SUGAR REDEVELOPMENT IN BROOKLYN , NY

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ABSTRACT

A quick glance of the architectural details on the Domino Site A project at the Domino Sugar Redevelopment in Brooklyn, NY show a simple architectural precast concrete window punch project. Further investigation, however, reveals many challenges that would make the project, now known as 1 South First, very labor intensive and time consuming for mold building and production. The challenges include deep set windows that necessitate tall vertical concrete pours, varying window widths and heights, varying architectural features from elevation to elevation that reduce cooling loads from solar radiation, and jamb-free corners.

Time was of the essence, so supplementing a production plants' mold building process was essential to producing panels at an acceptable pace to supply the needs at the jobsite. In addition to that, the project team needed installation solutions that would decrease the overall construction duration of the project.

This paper details how 3D printing of molds for architectural precast concrete reduced production time, and how pre-glazing the panels at the production facility and a weld-free connection scheme reduced the enclosure time on site.

Keywords:

3D Printed molds, Pre-glazing, Weld-free connection, Molds, Domino, Acrylonitrile Butadiene Styrene (ABS)

HISTORY OF THE CONSTRUCTION SITE AND PROJECT BACKGROUND

Figure 1. Domino Factory as viewed from the water under the Williamsburg Bridge prior to selected demolition. Photo by David Shankbone/Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Domino_Sugar_Williamsburg_New_York_by_David_Shankbone.jpg)

The history of sugar refining at the Williamsburg waterfront site dates back to 1856. The refinery grew to the point that more than half of the sugar consumed in the United States in the 1920s was refined at this site and the factory employed over 4500 workers. For a number of reasons, production declined to a point and ceased in 2004. The property sat dormant until in the fall of 2012, when Two Trees Management acquired the property with plans to reconnect South Williamsburg to its waterfront while adding commercial, residential, office and park space. In September 2013, Two Trees began selected demolition of various buildings at the site to prepare it for development.

Figure 2. Rendering of Site A building on the left. Image courtesy of CookFox Architects.

In July 2016, a design contract was awarded to Cook Fox for the Site A building and a few months later, Gate Precast Company was brought on board under a Design Assist (DA) agreement for the architectural precast concrete exterior on the 42-story building.

At this time, it should be noted, 3D printing of molds for precast concrete was just a concept in a research project at Oak Ridge National Laboratory (ORNL) in conjunction with the Precast/Prestressed Concrete Institute (PCI). Molds for concrete had not even been designed at that point, let alone fabricated or tested. An appropriate material for the print had not even been determined.

BACKGROUND OF 3D PRINTING OF CONCRETE MOLDS

Additive manufacturing (AM), or 3D printing, consists of adding material layer by layer to produce the targeted final shape. In the early 1980s, AM processes were primarily used for rapid prototyping; that is, quickly "print" a part for rapid development of prototypes so these could be tested for form, fit, and function. In 2014, ORNL conducted evaluations in which it reinforced polymers for AM with carbon fiber (CF) to significantly improve the polymer properties (Love et al 2014)[1]. More specifically, ORNL selected acrylonitrile butadiene styrene (ABS) because it was widely used with 3D printers and reinforced the ABS with 13% CF. The carbon fiber altered in-plane properties of 3D-printed ABS; that is, it increased the strength and modulus of elasticity, reduced the coefficient of thermal expansion (CTE), and increased the thermal conductivity. The last two significantly improve geometric accuracy because they minimize thermal gradients that lead to distortions (e.g., curl and warp) in the printed part. This in turn made large-scale AM feasible, because cumbersome mechanisms to reduce thermal gradients, such as printing inside ovens, were no longer needed. Subsequently, ORNL collaborated with many industry partners to print large parts such as a Shelby Cobra[2], molds for wind turbines (Post et al 2017)[3], and a house and an electric vehicle (Biswas et al 2016)[4] among other projects (Figures 3 and 4).

Figure 3. 3D printed Shelby Cobra (right) and mold for wind turbine (left).

Figure 4. 3D printed Additive Manufactured Integrated Energy (AMIE), which connected a natural-gas–powered hybrid electric vehicle to a high-performance building that produces, consumes, and stores renewable energy.

In 2015, ORNL and PCI were awarded funds to develop the next generation of precast insulated wall panels. A component of this project included evaluating the feasibility of printing molds for precast concrete because the precast industry was facing a shortage of skilled carpenters that could manufacture molds out of traditional materials such as plywood. PCI selected the cornice shown in Figure 5 as the design that it wanted to assess. Thermwood and TruDesign manufactured the prototype 12-inch deep mold shown in Figure 6 by printing ABS that was reinforced with 20% CF, and machining the “corduroy” finish with a computer numeric control (CNC) router. Figure 7 shows the final prototype mold and the quality of the smooth surfaces. Gate Precast cast more than 40 concrete parts with this mold (Figure 8) and determined ABS/CF to be a highly durable material.

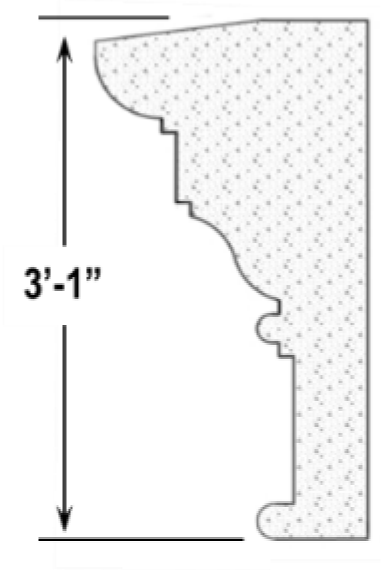


Figure 5. Cross-section of cornice design that PCI selected for the 3D printed mold tryouts.

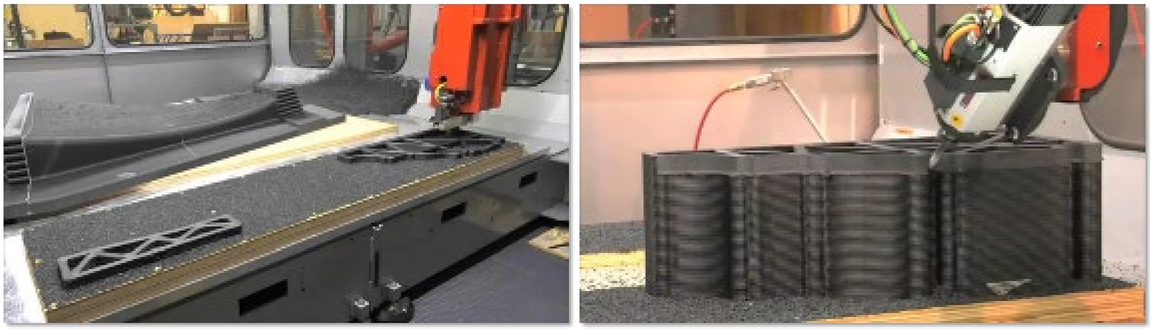


Figure 6. Left: printing of the two pieces needed for a prototype 12-inch deep cornice mold using ABS and 20% carbon fiber. Right: machining of the surface of the 3D printed mold to remove the "corduroy" surface with a CNC router.

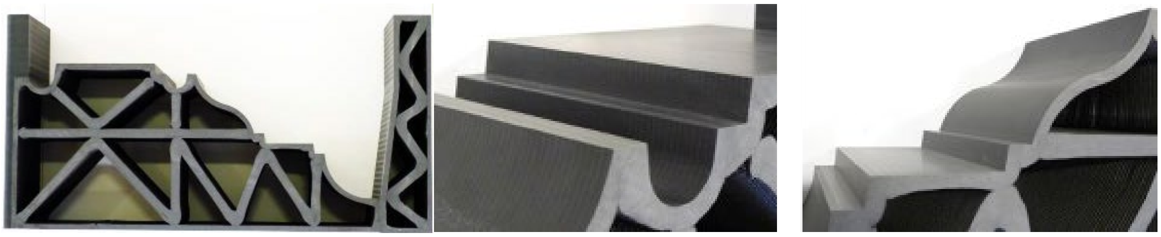


Figure 7. Prototype 12-inch deep cornice mold. Middle and right images illustrate the smooth surfaces, sharp angles, and tight radius that were achieved in the prototype mold.

Figure 8. Precast cornice cast by Gate Precast using the prototype 12-inch deep cornice mold.

PRECAST DESIGN ASSIST ON THE DOMINO PROJECT

At the same time that the cornice mold was being tested for durability, Design Assist (DA) had begun on the Domino project.

The first DA meeting between Gate, CookFox, and Two Trees was November 2, 2016. This was the first of several meetings, phone calls, web meetings and email conversation to follow. The last DA meeting occurred on January 11, 2017 with final design assist documents following a few days later, using Building Information Modeling (BIM) to expedite the process.

During the first meeting, the precast design discussions centered on details such as panelization, weld-free connection design, optimizing mold usage, mock-up design, and pre-glazing. The first attempt at panelization on the project included 4 punched window openings per piece (Figure 9). After much design and testing, the 4-window idea was scrapped for a 3 and 2 window design. This was done to satisfy structural and shipping constraints.

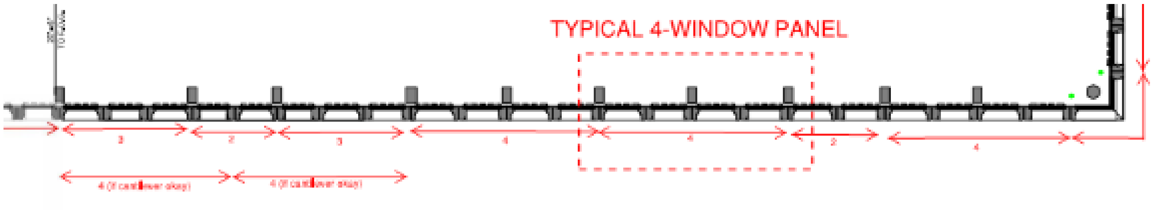


Figure 9. Plan view of residential tower showing panelization options

A weld-free, mostly bolted connection design is common in the NYC market and expected by most erectors in the area. It tends to be more labor efficient, allowing the crane to be unhooked sooner than with welded connections while allowing for some alignment adjustments after it has been set. Freeing the crane up quicker gives the opportunity for more panels to be set per day. Additionally, with the panels being pre-glazed, concerns for damage from weld splatter made bolted connections a near necessity to avoid excessive labor and material costs to protect the glass and frames.

To reduce mold quantities while still allowing for randomness in the building design, each window type and design was examined carefully to look for ways to reuse and save on mold work. This was achieved by making features in the molds that allowed them to be flipped 180 degrees and still work with the design, making common slopes on the North elevation and adjusting the south elevation's pattern. The east and west elevations had the most opportunity for optimization since these walls were the largest and required the largest number of different molds due to varying window widths. Window widths varied by only a ½" or an inch in some instances, but still required separate molds.

Through the DA process, over 100 mold types were eliminated from the project. While quite admirable, plenty of mold work remained. There were certain design elements that were dictated by locations of interior demising walls, building code, structure and aesthetics that did not allow for changes, resulting in still a significant number of different window widths.

The mockup design needed to be a combination of the different features and elevations. The design incorporated a corner piece that consisted of a 6-foot sequentially poured return leg with no corner mullion, edge-to-edge glass, and the entire single window surround for the East and West and partial for the North and South elevations (Figure 10). It was designed to be self-supporting with bracing connecting back to a slab. Consideration was given to the use of 3D printed molds, but time constraints did not allow it. The mockup was built with wood molds (Figure 11) and delivered and erected onsite April 21, 2017 (Figure 12).

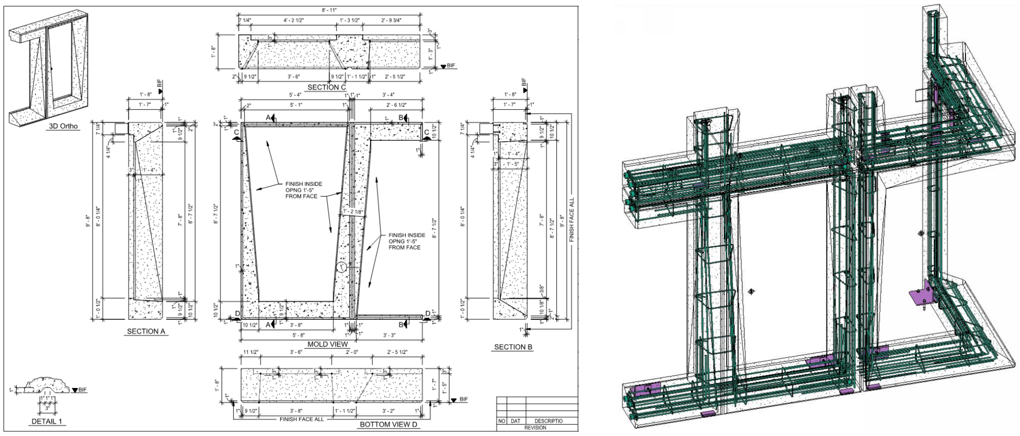


Figure 10. . Mockup drawing and reinforcing and connection rendering

Figure 11. Wood molds for mockup

Figure 12 Onsite mockup

WORLDS COLLIDE

In spring of 2017, after the DA process and mockup was complete, an active research project and a real construction project with an aggressive schedule began to converge. The printed mold for the cornice had been used successfully pouring (40) concrete pieces with no deterioration evident on the casting surface. There was no indication that the mold would not hold up for many more pours, so ORNL asked the advisory team for a design of a larger precast piece. The preference was a relative complex design that would be used in a somewhat high profile construction project.

The logical candidate would have been the Domino mockup, however, that ship had already sailed. The project still seemed like a great candidate for a scaled-up trial of a printed mold. It was a high-profile Brooklyn, NY project with a challenging volume of mold work, deep-set windows, formed with a lightly etched, white concrete mix. Since the mockup was not an option, thoughts turned to making one mold for the project and a meeting was set up for May 5, 2017, to discuss which mold would make the most sense to try to print.

Discussions quickly progressed to the point of a scenario where all of the molds for the 42-story building would be made by ORNL as a research project. This would surely prove the viability of the use of the technology. Eventually, this would work its way back down to the point where 80% of the residential tower panels were poured utilizing 3D printed molds, which was still a significant scale-up considering that the technology had only been proven successful on a one foot section of a cornice at that point.

So, Gate left the May 5th meeting with much to think about. On the one hand, 3D printed molds could be the solution for a large, mold-intensive project. On the other hand, the process was experimental and this was a real construction project with a real schedule and delay consequences. Production needed to begin in September to meet the schedule, so there was little time for trial and error.

Questions left to be answered:

- What material should be used for the print?
- How thick should the walls of the mold be?
- What do the wall deflections need to be limited to?
- What are the tolerances?
- What would the internal bracing look like?
- How do you attach the mold to the casting bed?
- How smooth does it need to be?
- How will sloped and horizontal surfaces be printed to keep the print from collapsing?
- How will vibrators be attached to the mold to vibrate the air out of the wet concrete?
- Will the vibrators damage the mold?
- Once a design has proved successful, can ORNL keep up with production?
- Above are some of the known unknowns. What are the unknown unknowns?

"…there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know." Donald Rumsfeld, shortly after 9/11/2001[5]

Despite the number of known, as well as unknown, unknowns with the 3D printed mold concept, Gate proceeded about a month later to partner with ORNL under a Collaborative Research and Development Agreement (CRADA) and PCI. The slow, calculated pace of the research and development world had collided with the time-is-money world of building construction and plant production.

PRECAST FAÇADE ENGINEERING DESIGN

With only three months from concept to production, the precast concrete design began. Multiple challenges still existed in the design of the façade despite the DA process. These challenges included:

- limited space and use of weld free connectivity
- engineering of corner panels
- completion of mold drawings parallel with submittal documents

New York riverfront real estate is "pricy". To maximize habitable floor space, precast connectivity was limited to only 3" around the concrete deck perimeter. Views of a typical load bearing and tie back connection are shown in Fig. 13 & 14, both occurring within 3" of the concrete deck edge.

In addition to spatial constraints, as stated previously, all connections were to be weld-free to aide in both erection expediency and prevent damage to the pre-glazing within the panels. Weld-free connections can occur within 3" of the concrete deck perimeter but only with good control of field and plant embed placement. There simply is not a realistic weld-free resolution when a combination of field and plant embed tolerance exceeds more than ~1".

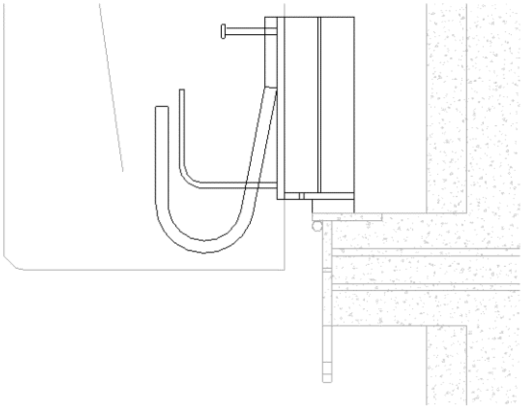


Fig. 13 Gravity load resisting connection

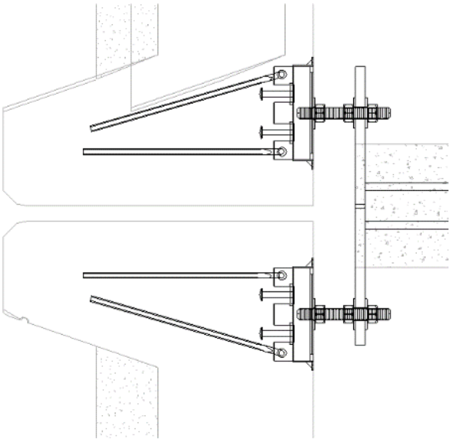


Fig. 14 Lateral load resisting connection

The corner panels were an architectural focal point in the façade. They were no less a focal point in engineering as an inordinate amount of labor was expended to find workable engineering solutions regarding connectivity and panel stresses. There were four substantially different corner panel scenarios - one at each of the northeast, northwest, southeast and southwest corners all with varying head and sill geometry. An example of a southwest corner panel with a temporary brace in both exterior, photographic view and interior drawing view are shown in Figures 15 & 16.

Fig. 15 Southwest corner panel exterior photographic view

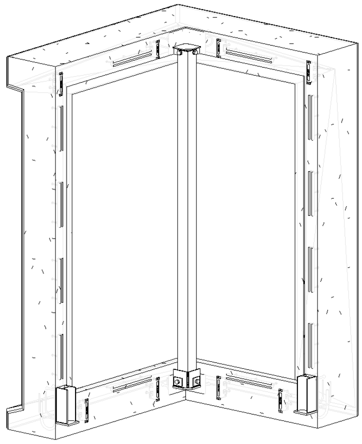


Fig. 16 Southwest corner panel interior drawing view

Corner panel connectivity was problematic due to lateral differential floor-to-floor drift. Horizontal slots alleviate in-plane precast stresses on normal wall panels due to in-plane movement of the structure; however, there was no legitimate way to release a corner panel in two orthogonal axis. One exterior elevation of the corner panel will undergo out-of-plane forces. An investigation of multiple connection scenarios occurred at the corner units with a goal of minimizing concrete stresses at the exposed surfaces. Unorthodox panel geometry combined with lateral building movement initially pointed toward a novel connection approach. An approach simplistically referred to as "cantilevered" seemed a promising idea. This notion of connectivity would "fix" the panel upon the supporting floor somewhat akin to a "tripod" and avoid any connectivity whatsoever to the floor above. This would allow lateral differential floor-to-floor movement to occur with little impact upon the corner precast panel stresses. After exhaustive study, it was concluded that a "cantilever" method of connectivity was not feasible. There is simply no reasonable way to utilize weld-free connections at a corner panel under multidirectional wind using only a 3" perimeter of concrete deck.

Upon forgoing ideas of a "cantilever" method of connectivity it was determined a more typical connection method would be necessary; therefore, corner panels would need to withstand lateral differential floor-to-floor drift. With this chosen connection scheme, lateral building movement became a considerable concern in the corner panel design. Wind tunnel testing provided cladding pressure values. The Structural Engineer of Record provided an anticipated 50-year wind drift of h/595. Precast stresses were generated based upon panel moments and cross sectional properties as shown in Figures 17 & 18.

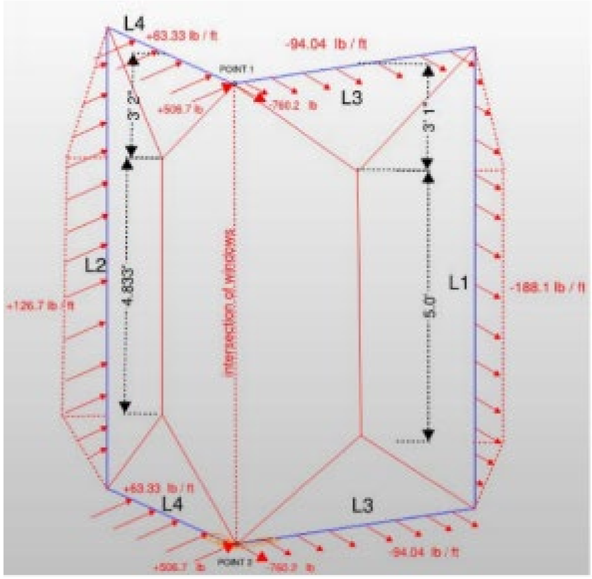


Fig. 17 Wind forces at corner panel

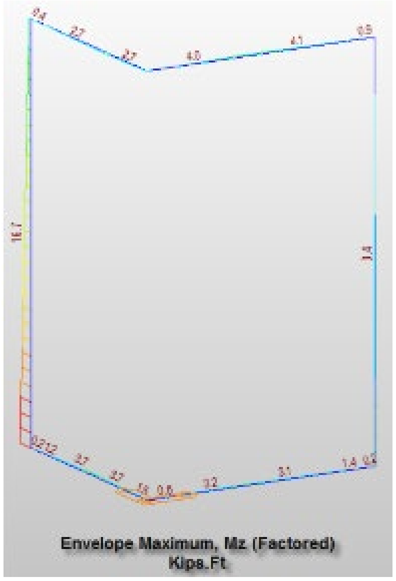


Fig. 18 Moments at corner panel

In many instances, concrete flexural tension stresses exceeded 5(f'c) which is considered the level of discernable cracking[6]. To overcome excessive stresses, mild steel reinforcing was utilized accordance with ACI 224-01, which stipulates both crack control criteria and a guide to crack widths based upon exposure condition[7]. As a factor of safety, all reinforcement in corner panels has a galvanized finish as a measure of corrosion resistance.

Running parallel to the formidable engineering effort was the choice to use large-format 3D printed forms. This added a facet of work to occur alongside all other modeling and engineering functions. Window openings were studied, altered and confirmed such that the forms could be utilized in two orientations. Forms described as A shaped for one window could be used as a V shape in another window. The manipulation of the façade to use variations in orientation enabled the forming effort to be cut in half.

Form manufacturing and construction could not be met if design data had to be re-created at every stage. Gate Precast had to collaborate with forming partners in regards to data exchange. It was a learning process along the way to turn voids in a Revit model into a usable form in the production facility in a timely and efficient manner as shown in Figures 19 & 20.

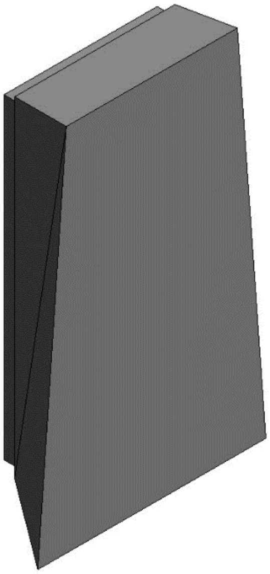


Fig. 19 Void in Revit model at window location

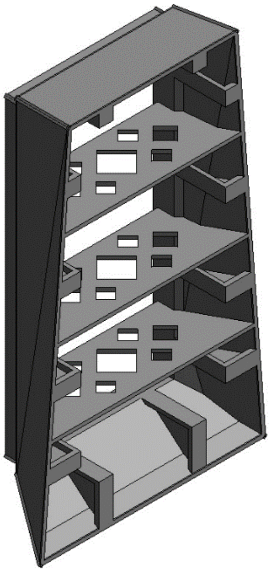


Fig. 20 Final model for use of printer

MEANWHILE BACK AT ORNL…

While precast design was ongoing, ORNL had 3 months from concept to production also.

The team decided to use ABS reinforced with 20% carbon fiber because of its previous successes printing large parts with this material and because the team was comfortable with its durability. A trial was conducted with glass fiber because it is more economical than carbon fiber; however, although the team had previously used this material, the printer had difficulties with it on the day of the trial and the team chose to stick with ABS/CF not to jeopardize the deliverable dates.

After several trials using Cincinnati's Big Area Additive Manufacturing (BAAM) machine that aimed to simultaneously optimize reducing the amount of printed material and minimizing underfilling or voids between printed layers (Figure 21), the team opted to use a 0.4" diameter extrusion nozzle that produced a 0.5"-wide bead. In general, two beads were used to make 1"-thick walls (Figure 21). Overruns or extra material was needed to machine the "corduroy" surface with a five-axis CNC router. In general, horizontal surfaces were printed with ~0.3" overruns and non-horizontal surfaces had ~0.2" overruns. The bottom of the mold also included extra material that was machined to ensure that the mold had a flat bottom surface for even bearing on flat casting tables that created a good seal and avoided concrete seepage. Figure 22 describes the design of corner overruns.

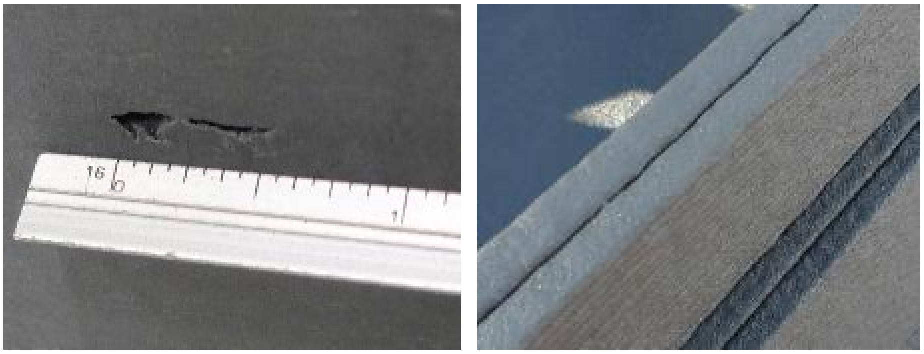


Figure 21. Left: void between printed layers caused by underfilling. A method to minimize these voids is to increase the nozzle size and thus the amount of printed material. Right: typical walls were 1" thick that were made of two 0.5"-thick beads.

Figure 22. Overrun or extra material printed at corners (left image) so that the “corduroy” finish (middle image) can be machined to generate the desired corner shape (right image).

Finite element analyses were conducted to determine the amount of deflection that the 20”-deep molds could experience due to the pressure exerted by the concrete on the mold. Results indicated that the defection was minimal (Figure 23) and that braces were not needed. However, the team decided to include braces so that these could be used as lifting points and would add extra rigidity to the part that would prevent deflection during transportation. Wood and steel braces were considered to decrease cost by reducing printing time and material (Figure 24), but these were discarded because of the expansion and contraction of the wood when the molds were stored outdoors and because inserting these braces during printing required precise timing. Thus, the team settled on printing the braces as shown in Figure 24.

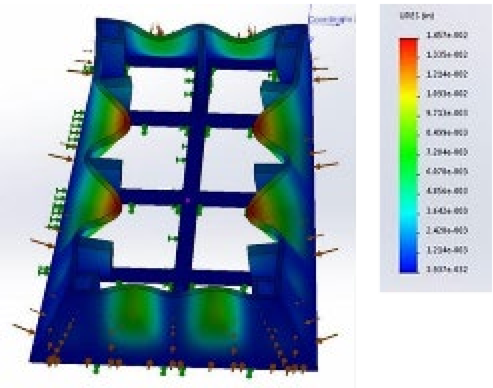


Figure 23. Results from finite element analysis of mold printed with ABS and 20% carbon fiber showed minimal deflection due to the pressure exerted on the wall by the concrete. Nevertheless, the team decided to include braces in the final design because these would add rigidity during transportation and serve as lifting points.

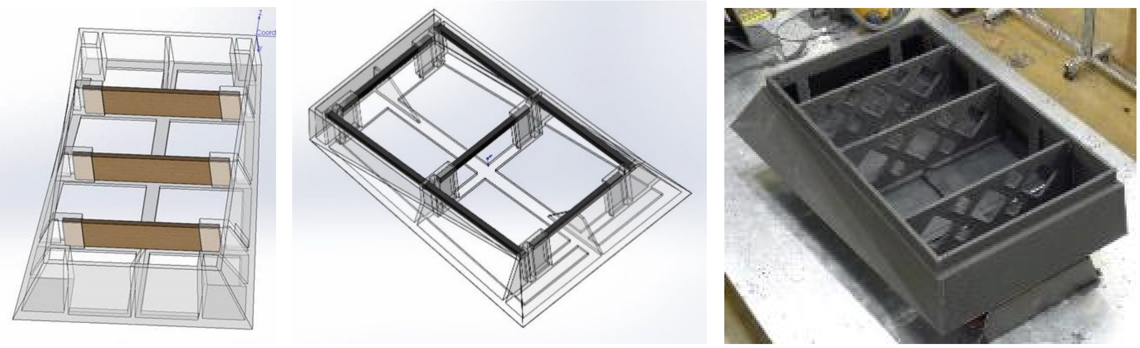


Figure 24. Left and middle: initial designs had wood and steel braces to reduce printing and material. Right: braces were printed in the final design since this allowed the part to be printed without interruptions.

To attach the molds to the casting bed, as shown in Figure 25, initial designs included a bottom flange so the mold could be fastened to the casting bed. However, the team discovered that the adhesion between printed layers was not strong enough to resist the vertical forces that were exerted during demolding. Therefore, hold downs were used to keep the molds in place by connecting the hold down to the top of the mold and the casting bed (Figure 25).

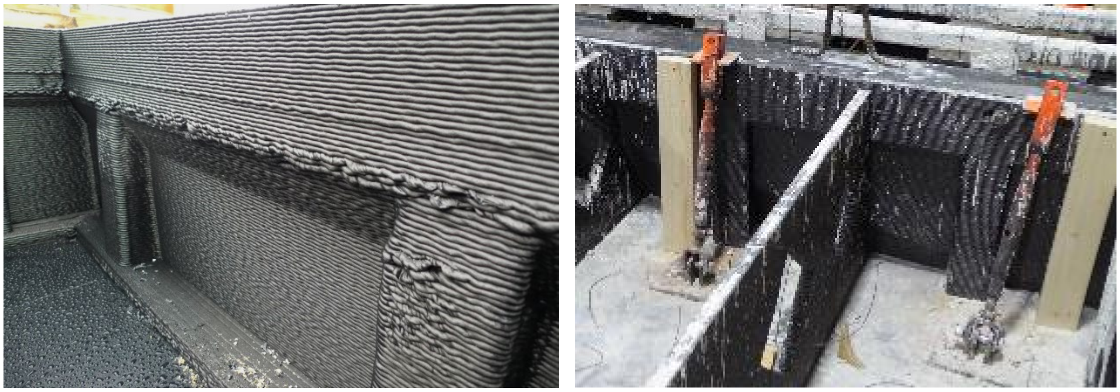


Figure 25. Left: in initial designs, a flange was printed at the bottom of the molds to attach them to the casting bed. Right: the final design used hold downs to keep the molds in place by attaching the hold down to the top of the mold and the casting bed.

The mold design for the north side of the residential building presented special challenges because it included surfaces that were steeper than 45 degrees and cannot be printed as self-supporting. Thus, these almost horizontal surfaces required that a supporting structure be printed underneath (Figure 26). The horizontal surface was initially printed with the simple toolpath shown in Figure 26. After machining the team discovered that there were large voids between the printed layers. As shown in Figure 27, these voids were filled with a 2-part epoxy; however, the gaps may have been too wide for the filler, the voids reopened, and residues in the voids stained the concrete. The team switched to a "fence" pattern (Figure 28) that increased the amount of deposited and packed material and reduced the number of voids.

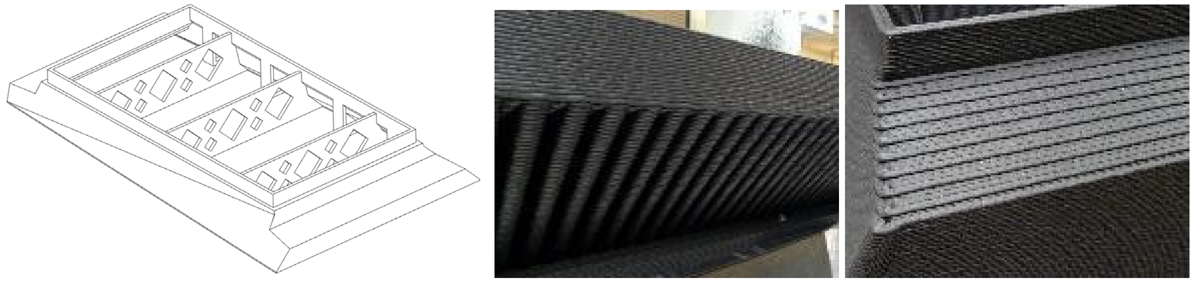


Figure 26. Left: mold design for north side of the residential building. Middle: supporting structure printed underneath the horizontal mold surfaces. Right: initial printing pattern that was used at the horizontal surfaces.

Figure 27. Left: horizontal surface of north mold after machining showed large voids between layers. Middle: voids were filled with 2-part epoxy. Right: voids reopened and bleeding of concrete in the voids caused dark lines in the concrete.

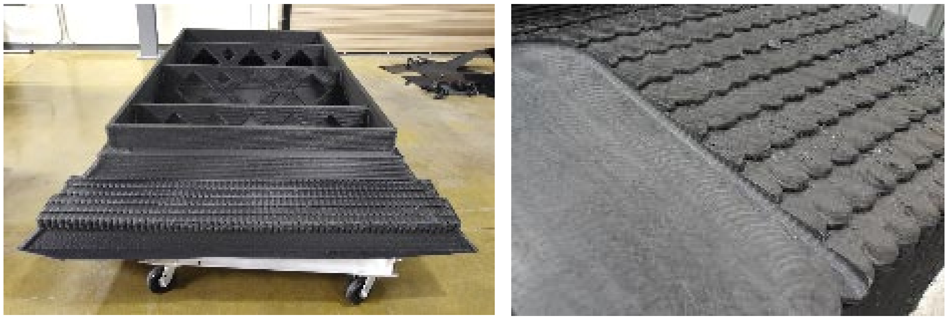


Figure 28. A "fence" printing pattern was used on the horizontal surfaces of the north mold to pack more printed material and reduce the potential for voids.

Because the north molds required extra material to support and minimize voids at the horizontal surfaces, the amount of time that it took to print a layer was relatively long compared to that of the other mold designs. This extra printing time created residual stresses that warped the corners of the mold as shown in Figure 29. The quickest fix to this problem was to print additional material to the bottom of the mold that would compensate for the warping when the bottom of the mold was machined.

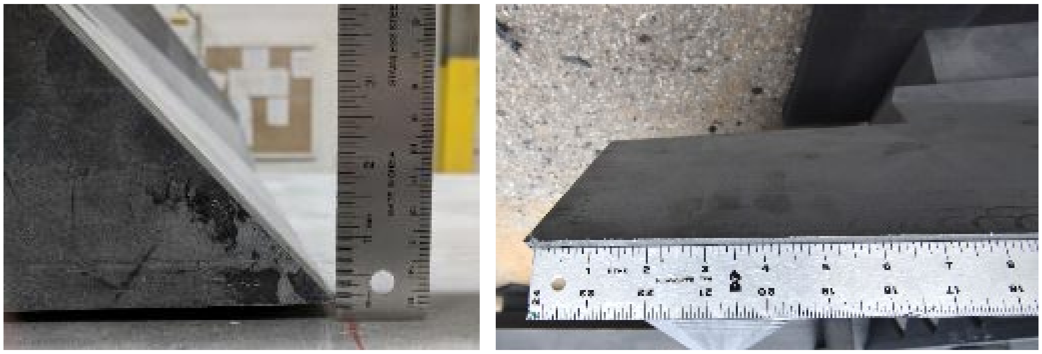


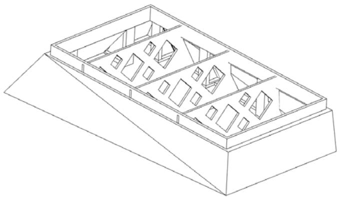
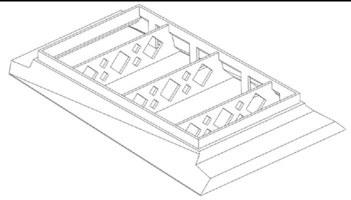
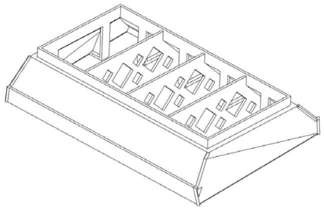
Figure 29. Left: corners of the north molds warped because of high residual stresses that were generated by the long layer times needed to print the support and extra material for the horizontal surfaces. Right: additional material was printed at the bottom of the mold to offset warping at the corners when the bottom of the mold was machined.

As shown in Figure 30, voids or defects appeared in the molds throughout their use at the precast plant. If the voids were small, the staff at the precast plant let them get filled with concrete and continued using the molds. If the voids were large or dents were accidentally made during handling, these were fixed by applying a fiberglass reinforced filler or installing ABS with a "welding gun".

Figure 30. Left: small gaps that emerged between the printed layers and got filled with concrete did not affect the finish of the concrete parts. Middle and right: dents and larger gaps were fixed with a fiberglass reinforced filler or ABS that was applied with a "welding gun".

Table 1 summarizes the shapes of the molds, their sizes, amount of printed material, printing time, and machining time. Note that the designs of these molds were not optimized given the time constraints. Therefore, there is room to reduce the amount of material and thus the printing time and ultimately bring down costs.

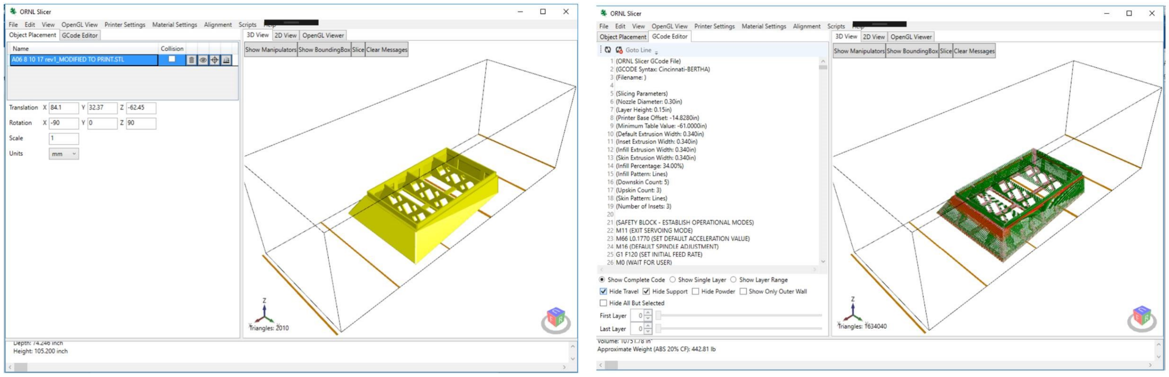
Table 1. Summary of the mold designs that were printed for the residential section of the Domino building.

Parameter	**East/West**	**North**	**South**
Size	~5'-9"×~8'-8"×~1'-4"	~5'-9"×~9'-8"×~0'-10"	~5'-9"×~9'-0"×~1'-4"
Printed material (lb)	~540	~450	~610
Printing time (h)	~8	~8	~8.5
Machining time (h)	~6	~7	~7
Mold design			

BIM DATA TRANSFER

Sharing models with the design team allowed the utilization of the Revit model as a template for the 3D printed molds. It also allowed the mold models to be "installed" into the project model to make sure the molds were exact before printing. Using Revit panel families with parameters setup for all the dimensions, locking some and freeing others to flex, allowed for easy adjustments. Then using voids with size parameters to cut the windows out of the panel families, created the punch window system. Planning ahead and using this method the panel families were used to convert the voids in the Revit panel families directly to solids, which is what is needed to start the mold files. This eliminated the step of redrawing all the window molds, increased the accuracy of the drawings, and allowed for a quick quality check of all molds. The converted solids represented the finished product (CNC version).

ORNL used the information that Gate provided to transform the data into a stereolithography (STL) file and load into the ORNL slicer program establishing the final toolpaths, or g-code (Figure 31).[8]



A06 8 10 17 rev1_MODIFIED TO PRINT.STL

Translation X 84.1 Y 32.37 Z -62.45
Rotation X -90 Y 0 Z 90
Scale 1
Units mm

Triangles: 2010

Depth: 74.246 inch
Height: 105.200 inch

```
(ORNL Slicer GCode File)
(GCODE Syntax: Cincinnati-BERTHA)
(Filename: )

(Slicing Parameters)
(Nozzle Diameter: 0.30in)
(Layer Height: 0.15in)
(Printer Base Offset: -14.8280in)
(Minimum Table Value: -61.0000in)
(Default Extrusion Width: 0.340in)
(Inset Extrusion Width: 0.340in)
(Infill Extrusion Width: 0.340in)
(Skin Extrusion Width: 0.340in)
(Infill Percentage: 34.00%)
(Infill Pattern: Lines)
(Downskin Count: 5)
(Upskin Count: 3)
(Skin Pattern: Lines)
(Number of Insets: 3)

(SAFETY BLOCK - ESTABLISH OPERATIONAL MODES)
M11 (EXIT SERVOING MODE)
M66 L0.1770 (SET DEFAULT ACCELERATION VALUE)
M16 (DEFAULT SPINDLE ADJUSTMENT)
G1 F120 (SET INITIAL FEED RATE)
M0 (WAIT FOR USER)
```

● Show Complete Code ○ Show Single Layer ○ Show Layer Range
☑ Hide Travel ☑ Hide Support ☐ Hide Powder ☐ Show Only Outer Wall
☐ Hide All But Selected
First Layer 0
Last Layer 0

Triangles: 1634040

Volume: 10751.78 in^3
Approximate Weight (ABS 20% CF): 442.81 lb

Figure 31. Mold in ORNL Slicer (left). Toolpaths for mold (right)

Data from the BIM was also used to locate the printed mold on the Thermwood router or CNC using a Faro laser tracker and to determine the toolpath pattern.[8]

PRODUCTION

Despite the many hurdles, production and erection began on time (Figure 32). As of this writing, the precast has all been cast and erection is over 50% complete (Figure 33). Thirty-seven (37) 3D printed molds were used with half being fabricated by ORNL and half being fabricated by a commercial manufacturer, AES, in Akron, OH. The molds vibrated and consolidated very well, resulting in very minimal bugholes despite the 20” deep vertical pours and smooth acid-etched finish (Figure 34). And corners are crisper than with wood molds.

Figure 32. Twilight erection of 2-window unit

Figure 33. Construction progress as of March, 2019

Figure 34. West Elevation panels as erected showing deep recesses and no bugholes.

Due to the weld-free connection schemes, panels are being installed in approximately 30 minutes each, where one hour would be the norm.

The pre-glazing in the plant has gone well and knock-on-wood, no windows have been broken in transit. (Figure 35).

Figure 35. Pre-glazed panel at production yard ready for shipment

CONCLUSIONS

The weld-free connection schemes allow panels to be erected in about half the time.

3D printed molds cost about $9000 bought commercially, whereas a fiberglassed wood mold would cost about $1500. A couple of the 3D printed molds were used over 200 times on the project without interruptions for resurfacing and could go longer if the project design required it. The fiberglassed wood mold would usually only last 20-30 pours before needing to be recoated. It should be duly noted that due to the time restraints, having only 3 months from concept to production, these molds were not optimized. They could have twice the material in them than what was actually needed, plus a lower cost material may have worked as well.

There are benefits that the 3D printed molds provided that are difficult to put a price tag on. For example, production efficiencies were recognized since casting space was not used for building the numerous molds. The 3D printed molds were practically plug-and-play reducing lost production days with mold changes. Additionally, they were more rigid than their wood counterparts allowing them to be more easily rotated and moved for the frequent architectural configurations changes.

Pre-glazing allowed months to be cut off of the erection schedule and interior work to proceed during winter and inclement weather. The quote below from the owner's representative seems to speak for itself.

"We never explored traditional delivery. It's hard to quantify the time savings because you would have to figure distributing to every floor and staging in the apartments. It would have massively delayed our ability to start the interiors program. The use of the hoist alone would have prohibited other trades from doing their work not to mention the added duration to occupy each apartment and install the window which is probably an hour per window." Hale Everets, Two Trees

FUTURE RESEARCH

To facilitate more wide scale adoption of 3D printing of molds in the precast concrete industry, cost reduction will be paramount. Using a lesser amount of a less expensive material will accomplish this.

Alternative materials include bio-sourced, renewable materials. ORNL has successfully printed polylactic acid (PLA) that is reinforced with either cellulose nanofibrils, bamboo fibers, or wood flour. These options are more economical than ABS/CF; however, evaluations need to be made to determine if these materials are durable enough to cast at least 20 concrete parts, which is what is typically expected from a conventional wood mold.

Other future assessments include recycling the ABS/CF molds that were manufactured for the Domino building. Techmer, a manufacturer of 3D printing material, will conduct evaluations to determine the effect of the concrete and release agent residues on the recycability of the ABS/CF material. Once the materials are re-ground, a percentage could be added to virgin material to reduce costs in subsequent printed molds.

Generative design programs continue to evolve and could aid in identifying areas to reduce material in the molds while maintaining their strength.

Durability has been proven to be over 200 pours using ABS with 20% carbon fiber. Further research could show that the molds may last 500 or 1000 or maybe even rival steel mold durability.

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