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PRECAST CONCRETE MOLDS FABRICATED WITH BIG AREA ADDITIVE MANUFACTURING

Alex Roschli*, Brian K. Post*, Phillip C. Chesser*, Matt Sallas*, Lonnie J. Love*, and Katherine T. Gaul*

*Oak Ridge National Laboratory, Manufacturing Demonstration Facility, 2370 Cherahala Blvd,
Knoxville, TN 37932

Abstract

The traditional process of making precast concrete molds requires significant manual labor. The molds are made using hardwood, cost tens of thousands of dollars, and take weeks to build. Once built, a mold will last 5-10 pulls before becoming too heavily degraded to continue use. With additive manufacturing, the same mold can be built in eight hours, post-machined in eight hours, costs about $9000, and is projected to last nearly 200 pulls. Oak Ridge National Laboratory has been working with Big Area Additive Manufacturing (BAAM) to fabricate concrete molds for a new high-rise apartment complex in New York. The molded pieces will form structural window supports for the hundreds of windows in building façade. The magnitude of window molds is where additive manufacturing can shine when producing the geometry. This paper will discuss the methods and findings of using BAAM to replace conventional precast concrete pattern making.

Introduction

Precasting concrete is the process of making a concrete object using a reusable mold, typically constructed with handmade wooden forms. This is in contrast to the traditional concrete process that involves pouring concrete into a custom, single-use mold on site. In the precast concrete process, a reusable mold is often housed in a factory and used to make 5-10 parts [1]. Pouring molds in a factory allows the concrete to cure in a controlled environment before being transported to the job site. The traditional method of making a precast concrete mold is very labor intensive. It involves many man hours to construct a mold from wood (Figure 1 and 2) by hand. Workers start with large sheets of plywood and cut them down to the sizes needed for the mold and discard the excess wood which is very wasteful. All of the wooden pieces must be precisely cut to size and assembled properly so that it meets the required tolerances for the design. A mold that isn't perfectly sized and aligned must be fixed or discarded. A finished mold that is approved for production typically lasts about 5-10 pours, or uses, before the mold has degraded outside of the geometric tolerances. Once the mold has degraded, it is trashed, and a new mold must be made. Starting the laborious and wasteful process over again.

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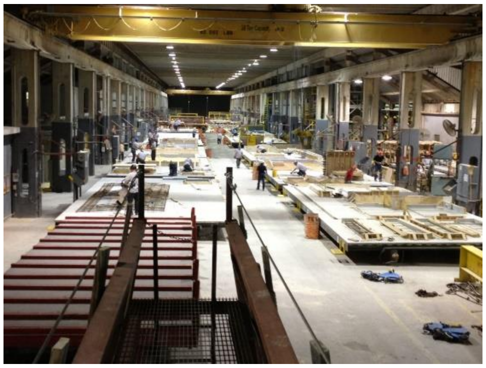

Figure 1: Factory where traditional precast molds are assembled

Figure 2: A traditional manufactured concrete mold using wood

Additive Manufacturing (AM) is the process of growing a part layer by layer by adding material as opposed to traditional manufacturing, which uses subtractive processes, such as milling, to cut away material from a billet to obtain the desired geometry. Big Area Additive Manufacturing (BAAM) is large-scale AM, which enables the manufacture of parts eight feet wide, twenty feet long, and six feet tall. BAAM uses pelletized thermoplastics as a raw material and can output up to 100lbs an hour. With an extrusion rate orders of magnitude greater than other AM processes, BAAM can build large, complex molds quickly and consistently. Because pelletized materials are cheaper than filament based materials, BAAM offers a significant cost savings over other polymer based extrusion processes.

Domino Sugar Refinery

Oak Ridge National Laboratory (ORNL) has partnered with Gate Precast Company to build the precast concrete molds that will be used to create the concrete façade of a high-rise apartment building (Figure 3) in Brooklyn, New York City, New York.

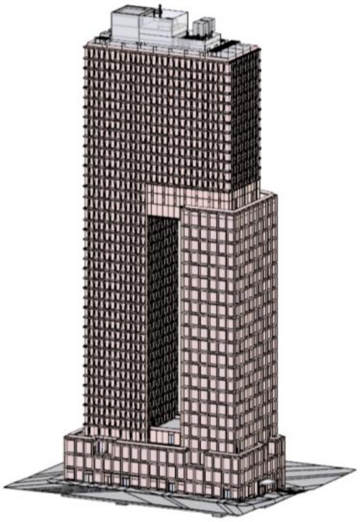

Figure 3: Drawing of the new building to be made with AM concrete molds

The new development will house recreational space on the lower floors and a residential space in the upper floors, coming together to enhance the historical Domino Sugar Refinery complex that has been an icon of the Brooklyn Waterfront since 1882. The façade is primarily constructed with precast concrete patterns that surround the windows (Figure 4). There will be 993 of these precast concrete panels making up the 42-story building.

Figure 4: Rendering of the concrete patterns with inset windows

Design of Concrete Molds for AM

Traditionally, most precast molds are used sparingly and not for large-scale production. Each mold is made by hand out of wood, which introduces variability. Therefore, additive manufacturing with BAAM is a viable solution to the issue because BAAM produces highly replicable parts. However, the design of the precast molds had to be altered to make them printable. Overhangs were eliminated, walls were thickened, corners were overbuilt, and toolpaths were modified.

With BAAM, the overhang angle threshold is forty-five degrees from the vertical axis. Overhangs greater than this are considered a risk because they could cause the print to fail. Some of the concrete molds, such as the one seen in Figure 5, had overhangs that were not printable. To fix the issue, the wall was thickened such that it would grow inwards at a 45-degree angle until it was wide enough to support the overhang. Then the part was machined using a 5-axis mill to the correct dimensions. By combining additive and subtractive manufacturing, a geometry was achieved that would not have been possible with solely additive manufacturing. Additionally, material was still saved when compared to the subtractive methods traditionally used to produce molds similar to the one shown in Figure 5.

Figure 5: Concrete pattern that has an overhang exceeding 45 degrees from the vertical

The concrete patterns were printed using a 0.4” nozzle, which created a 0.5” wide bead, or layer width of a single line of extruded material. The nature of slicing for BAAM requires all paths to be a closed loop, meaning that no wall sections could be just one bead thick, and therefore, there must be an even multiple of bead widths. The result is that all walls had to be designed to be an inch integer in thicknesses.

The design for the panels needed to have perfect 90-degree corners so they can mate with one another during the assembly of the building. During the printing process, the bead coming out of the extruder gets pulled around the corner and creates a radius instead of a perfect 90-degree angle. This is continued with each layer of the material making producing a 90-degree angle impossible without a means of correction. To fix this, corners had to be printed with extra material, or be oversized, to ensure that there was enough material to cut away to achieve the desired, 90-degree geometry (Figure 6).

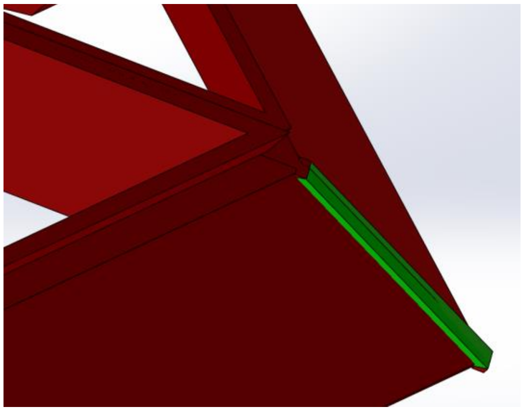

Figure 6: Green section representing an extended corner

The last design challenge was to fix the toolpath generation when slicing. Slicing software is used to create the toolpaths the machine follows from the CAD model of a part. The molds needed either large, flat surfaces to achieve desired geometries through machining, or the molds needed to have oversized corners to interface well with the casted panels. To get large flat surfaces, like that shown in Figure 5, a new method of filling surface had to be implemented in the ORNL Slicer. The part was designed with 0.001" thick gaps every inch to create a fence pattern that could be overbuilt to allow for a solid surface to remain after machining (Figure 7). Normally, something like this would be done with an infill pattern, but an infill with a surrounding perimeter creates porosity that would have to be filled after machining. Slicing software is designed to remove small gaps to optimize toolpathing. The optimization reduces the print time and the distance the extruder travels, but it also deletes the 0.001" gap in the design. To solve this issue, ORNL Slicer had to be modified to remove all optimization features and leave the 0.001" thick gaps so that the part would be printed exactly as designed.

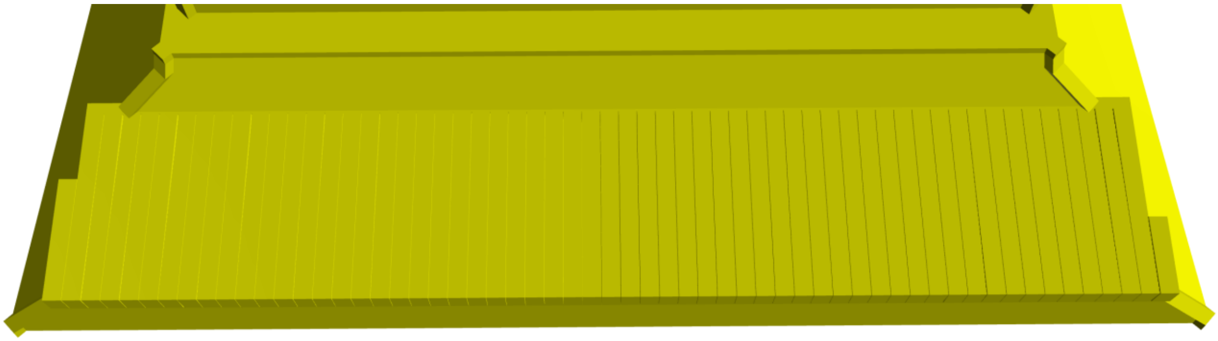

Figure 7: Concrete pattern with 0.001" thick gaps to force a down and back perimeter pattern

Printing of Concrete Molds

Molds were printed using a Cincinnati BAAM machine (Figure 8). The material used for printing was carbon fiber reinforced acrylonitrile butadiene styrene (ABS), a common thermoplastic. The thermoplastic is compounded with chopped carbon fibers by Techmer PM. The carbon fiber improves the strength of the material and reduces the coefficient of thermal expansion, so there is less warping for larger parts that would normally warp in neat ABS.

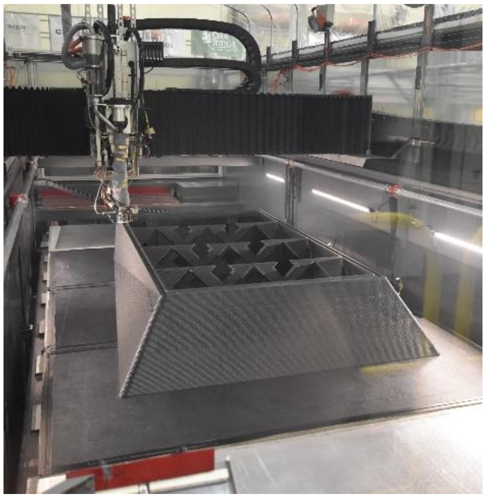

Figure 8: A mold printing inside a Cincinnati Inc. BAAM machine

The molds for the different panels took between eight and twelve hours to print and weighed between five hundred and eight hundred pounds. The larger molds had to be split into four sections because they would not fit inside the build volume of the BAAM system (Figure 9). These molds were split at the corners and then overbuilt to allow extra material to be machined away to leave flush faces to be joined. The smaller molds were able to be printed one at a time on the BAAM system. (Figure 10).

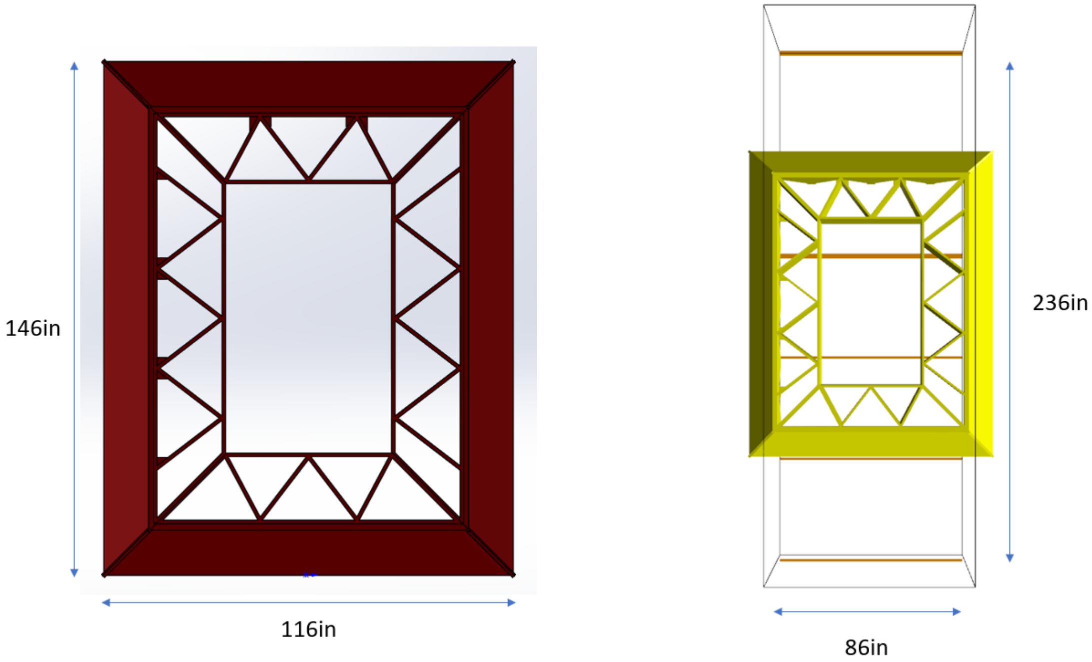

Figure 9: At left, overhead view and dimensions of the largest mold. At right, overhead view of the printer dimensions with the largest molded loaded

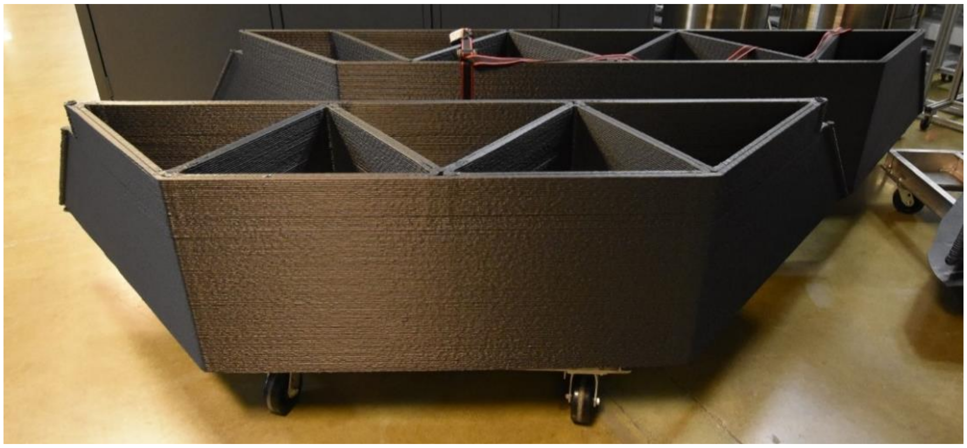

Figure 10: Two small pieces of a large mold split into four sections

Post-Processing of Molds

After a mold had been printed, the last step before handing off the printed part to Gate Precast Company was to post-process the mold. This step was completed at ORNL using a 5-axis CNC router. The 5-axes are necessary to achieve the desired geometries for the molds. Parts are transferred from the BAAM machine onto the bed of the router and aligned using a laser tracker.

Figure 11: Machining a concrete pattern

On the larger and longer molds, another obstacle was discovered. The addition of carbon fiber to the material was not enough to prevent warping on a ten-foot mold, and once printed, there was almost ¼" of warping (Figure 12). To fix this issue, the bottom of the molds was overbuilt to leave it thicker. Then the extra material was cut away from the bottom of the finished part. By cutting away the extra material at the bottom, the final mold was flat. Additionally, the mold was allowed to cool on the build platform for at least 12 hours to further prevent warping. This gave the mold time to reach a uniform temperature while being and held place by the vacuum of the BAAM's build sheets.

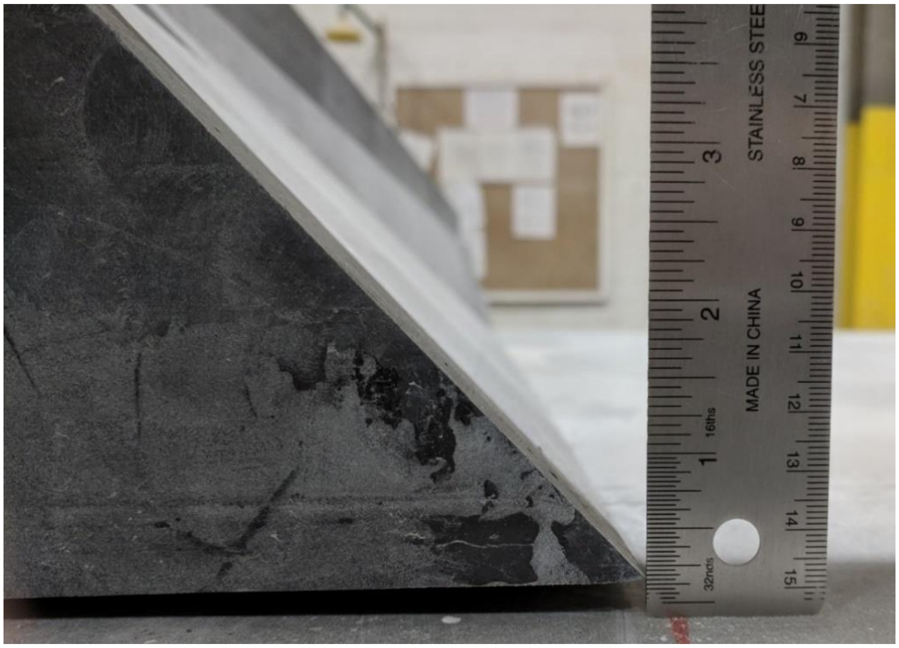

Figure 12: A warped corner of a concrete mold

The outer surface of 3D printed parts has a corduroy-type finish that is the result of round layers being stacked on top of one another. The outer mold surface must be smooth so that the concrete pieces pulled from the mold are smooth. During machining, porosity was encountered due to the nature of rounded beads being stack atop one another. To fix this, rods were made from the CF-ABS material and melted into the voids with a hot air gun, and then the molds were machined to tolerance (Figure 13). The remelting process is very quick and takes just a few minutes per mold.

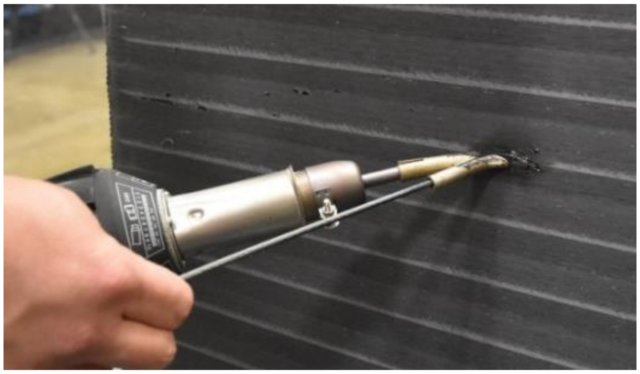

Figure 13: Re-melting polymer rods to backfill voids caused during machining

Pouring the Molds

Once molds were completed by ORNL, they were shipped to a Gate Precast Company facility for final inspection and pouring. Upon arrival, Gate Precast Company measured all molds for geometric accuracy. Molds must meet the required tolerances to be used on the production line. Molds were also checked for porosity so that concrete does not get into the mold. All of the 3D printed molds met the required tolerances and had no porosity issues.

The pouring process started by creating a large wooden form in the shape of the outer pattern geometry. This was essentially a large square box that can be made very quickly and inexpensively. The outer form won't last as long as the 3D printed mold, but it can be rebuilt easily. After the outer form has been constructed, the 3D printed mold was dropped down inside the form (Figure 14). Wooden forms are used because they can be made very quickly and inexpensively, though as with the wooden molds, they are wasteful.

Figure 14: 3D printed mold sitting inside wooden form

The next step was to pour the custom blend of concrete around the mold, and then the concrete is left to cure for 18 hours. After the concrete cured, the final part was pulled from the mold and inspected (Figure 15). Like the mold, the final part must be inspected to ensure an accurate final geometry and to ensure that there were no anomalies during the concrete curing process.

Figure 15: A completed concrete part that has been pulled from the mold

Comparison of Production Methods

This project uncovers new avenues for AM in precast concrete. It has shown that for larger projects BAAM is a more cost-effective method for producing the molds. For this project, producing the mold via AM cost about $9000 as compared to a cost $1500 to $1800 when making it conventionally with fiberglass and wood. To date, the AM molds have lasted for more than 190 pulls without degradation. A cost comparison can be seen in Figure 16.

	Traditional	BAAM
Cost/Mold	$1800	$9000
Pours per Mold	10	190
Cost per Pour	$180	$47.37

Table 1: A cost comparison of the molds

As illustrated by Table 1, there is significant cost savings when using the BAAM molds because of the longevity of the parts, which compensates for the increased cost of the AM molds. Additionally, since the molds are not made by hand but rather are made using a 3D printer, a 5-axis CNC, and a light coating, the consistency from mold to mold is significantly higher given that most of the work is done by a calibrated machine. A CNC machining process also takes less time than manually building the molds, and the router can machine the part within 0.005” of the desired dimensions [2], where traditionally making a mold would take approximately 40 hours, the AM process takes 8 hours to print and 8 hours to machine for a grand total of 16 hours to make a final mold. Figure 16 shows that over the entire mold, the accuracy was always within 1/16" of an inch. Because of the tight tolerances of the CNC router, all the 3D printed molds came out within spec and none were wasted.

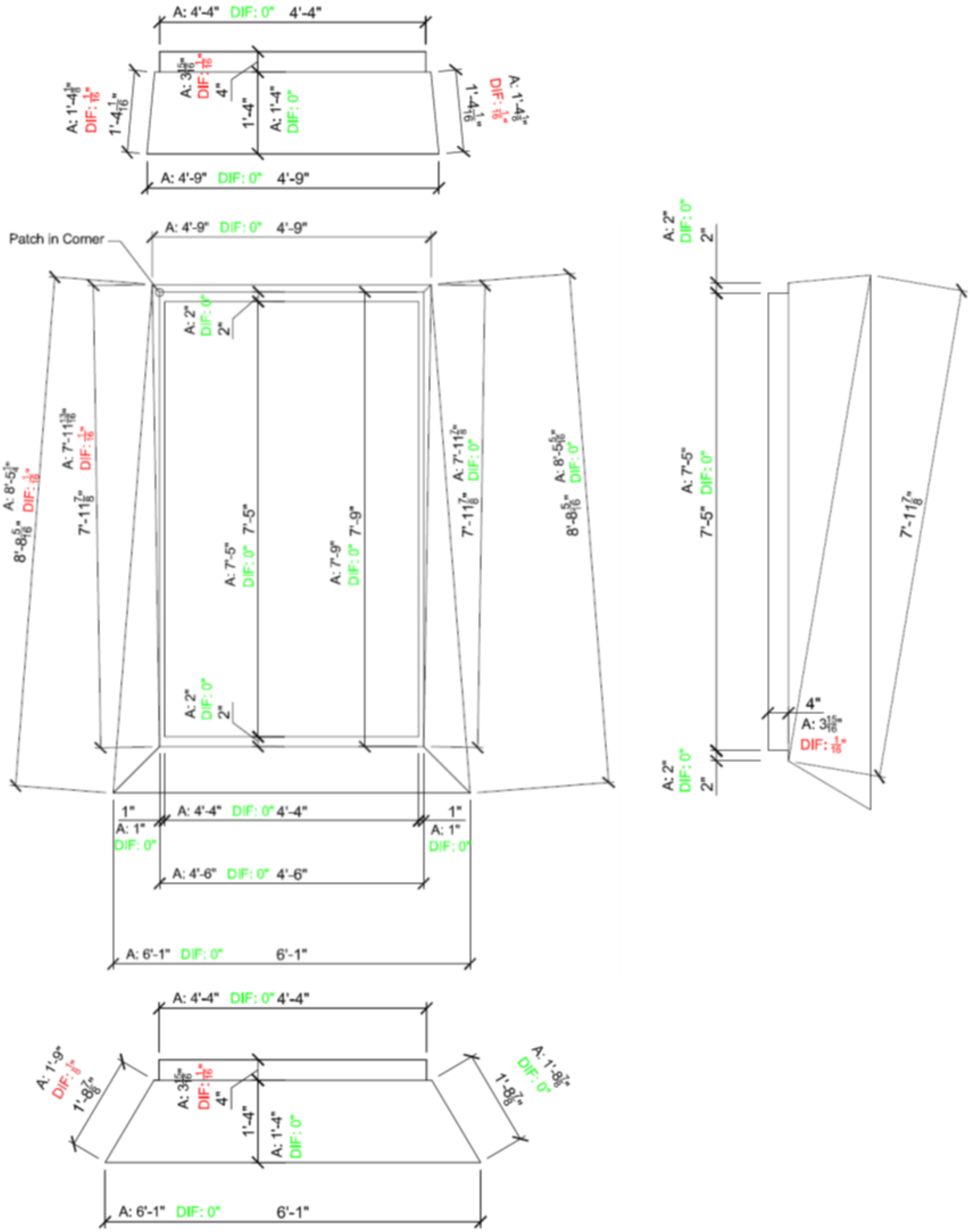

Figure 16: Accuracy measurements of a 3D printed concrete mold

Conclusion

The traditional method of making precast concrete molds for construction is a slow, labor-intensive, and wasteful process. Additive manufacturing has been applied to save time, money, and material while making molds with significantly increased longevity. With BAAM, complicated portions of a precast concrete mold can be printed from a carbon fiber reinforced ABS in just eight hours. That same mold can then be machined in approximately the same amount of time and be ready to for use almost immediately after fabrication. The finished molds have lasted 190 pours without degradation and are still in use today.

Acknowledgements

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