The Design and Fabrication of Variable Façade Panel Systems

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Abstract. This study explores how alternative molding methods can be utilized to construct a variety of prefabricated volumetric concrete panels for façades from a single digitally fabricated mold. First, precedents were studied and panel variability was classified into ornamental, geometric, or assembly categories. Then, a molding method was proposed that improves upon traditional processes. Traditionally, geometrically varied façade panels are realized through creating a single mold for every variant, which is inefficient and wasteful. The proposed method allows for reusability of a singular mold which can fabricate variated panels through utilizing interchangeable mold inserts. This proposal was tested on a small scale through creating rapid iterations of molds fabricated with Stereolithography (SLA) printing. Emerging big area additive manufacturing (BAAM) technology allows for the proposed methods to be utilized at the industrial scale where they can reduce the cost, labor, and time of fabricating varied concrete panels while also creating complex geometries.

Keywords: Variability, Precast Panels, 3D Printing Mold, Custom Repetitive Manufacturing, Facades.

1 Introduction

1.1 Limitations of Precast and the Case for Additive Manufacturing

Concrete precast building systems have become widely popular since the early 20th century (Sutherland, 2001). Adopting concrete prefabrication methods as an alternative to in situ casting has many benefits, one being increased productivity in construction (Nahmens et al. 2011). This increase in productivity typically only largely applies to the fabrication of standardized objects through restricting the variety of possible panel designs in order to simplify production. In addition, precasting is labor intensive. Oftentimes, formwork elements exclusive to the desired product are assembled on stationary tables by hand (Pan et al. 2019). This requires the utilization of skilled laborers and limits the ease at which complex geometries can be formed. From a different perspective, the use of standardized façade panels by designers simplifies production, but can lead to monotony and regularity amongst façades (Feng Li et al, 2020). Given those restrictions, if a designer requires panel variants on their façade, precasters would have to fabricate a different mold for every panel. Having to fabricate a large number of molds is both time consuming and costly. For instance, according to Love et al, the cost of fabricating a traditional wood mold can be around $3,000. Typically, that mold can only produce twenty panels before it becomes unusable, which means the cost per pour is $150 (Love et al, 2019). In a highly varied façade a mold may be used as few as once, meaning that the cost per pour becomes the full price of constructing the mold. Despite the increase in geometric complexity of façade panels as a result of computational design tools, precast concrete manufacturers at large do not currently have a strategy to fabricate complex and varied panels without fabricating a large amount of formwork. Therefore, there is a need to conceptualize alternative fabrication methods that allow for variable production of architectural panels without compromising fabrication efficiency. A possible solution to the inefficiencies of precasting can be found in digital fabrication (DF).

The exploration and application of DF for casting concrete has become a popular field of research and is widely referred to as Digital Fabrication with Concrete (DFC) (Asprone et al, 2018). Studies have been done on the applicability of a wide variety of methods to either fabricate the formworks of concrete through subtractive or additive processes, or to directly 3D print concrete. These include but are not limited to robotic hot wire cutting of polystyrene formwork (Martins et al, 2019), PLA fused deposition modeling (FDM) for creating one-off formwork (Jipa et al, 2019), Smart Dynamic Casting (SDC) of concrete (Lloret-Fritschi et al, 2017), and 3D concrete printing (3DCP) (Asprone et al, 2018). This study focuses on the production of formworks for precast concrete panels.

Existing DFC techniques that are concerned with the production of concrete formworks are successful in a number of ways. They succeed in casting geometries far more complex than those produced through traditional methods, and the labor required to assemble the form is reduced through automation of its fabrication. (Jipa et al, 2017) However, the methods are mainly used for bespoke fabrication and thus lack reusability since the forms can typically only cast one specific geometry. Many of the current bespoke fabrication methods eliminates the possibility of a variable product from a single mold print. Further, the vast majority of formworks created through these methods require time-intensive production. These shortcomings will prevent the current DFC state of the art from completely replacing the current precasting methods. However, the strengths of additive manufacturing (AM) cannot be ignored. AM can be applied to aspects of the currently existing precasting methods to improve the possible geometric complexity of cast objects. In fact, studies have been done that show when utilizing mold inserts fabricated through big area additive manufacturing

(BAAM) the cost per pour to produce a panel can be reduced by over a third (Love et al, 2019). While AM methods can be feasibly utilized for architectural scale production, additional design exploration is required to implement variability to the fabrication process.

1.2 Objectives

Given that neither the withstanding precast methods nor the emerging DFC techniques are able to cast a large number of varied products without fabricating a large number of molds, a new approach is needed. The question is how can panel variability be designed considering that digital fabrication will be employed for realizing the design?

This study aims to explore how a digitally fabricated mold can produce varied façade panels. The objective of this study is to formalize the way that variability in façade panels can be created considering digital fabrication techniques for realizing the panels. More specifically, our objective is to design and fabricate a variety of geometrically complex panels that are realized through interchangeable mold inserts. This new approach to precasting will allow for the rapid casting of varied products, which is a necessary step in making varied façade panels more accessible to designers. Computational design platforms namely Rhinoceros NURBS modeling platform are used for design, digital fabrication techniques, namely 3D printing, are used for prototyping. The methods are described in detail in the following section.

2 Methodology

The study began by classifying different types of variability using observations made on built facades. When succinct definitions of different types of variability were developed, the design and fabrication of façade panels and molds began. Two facades were fabricated through an innovative approach for creating variability, and were investigated further. The Le Vérone Building and the Perot Museum of Nature and Science were two case studies that we focused on since they both utilized mold inserts for creating variability through a single mold. These two case studies created the base for exploring the design and fabrication of variability. Inspired by Le Vérone Building's panels, Panel A was designed. It had a prescribed geometry which we introduced variability to through a new molding method. Inspired by the Perot Museum of Nature and Science, Panel B was designed. It had an opposite approach, in that the design was based solely around the new molding method. Rhino 3D was used for computational design, and custom repetitive manufacturing (CRM) with AM was used in fabricating the molds, which were then used to cast varied panels. For the casting we utilized Rockite expansion cement due to its fast set time, and because its mechanical properties are similar to that of ultra-high-performance concrete (Rockite Cement, 2017)(Portland Cement Association, n.d.).

2.1. Observing and Categorizing Variability

It is important to critically assess, rationalize, and provide definitions of variability before attempting to design and fabricate varied panels. To do so, general observations on built façade panel variability were made. While the variations between panels were unique from project to project, it was observed that there are similar overall strategies to create that variance. To start, every project's panel variants did not dramatically differ from other panels on their respective facades, there was always a holistic aesthetic. Further, variations can oftentimes be observed as a change in the size and/or distribution of the additions to and/or subtractions from a singular overall panel geometry. Panels may also vary through an elimination from or addition to the overall geometry of the panel. These observations are not, by any means, an all-encompassing list of the possibilities of creating variations between facade panels. However, it seems that there are two different broad classifications of variability amongst built facades: <u>ornamental variability</u> and <u>geometric variability</u>. While thinking on the possibilities of variability beyond modification of the panel's geometry or finish, a third classification was conceptualized: <u>assembly variability</u>.

- Ornamental variability occurs when panels have the same overall geometry but a range of different ornamentation on one or both of their surface(s).
- Geometric variability occurs when panels have a range of different measurements for their final cast panels. With this classification, the measurements of the outer boundaries of the panel changes between panel variants.
- Assembly variability refers to the panel's qualities upon on-site assembly. Similar to a brick that is agnostic to orientation in certain axes, a panel with assembly variability has a design that allows for it to be placed freely on a facade to create a number of different overall facade arrangements. The massing and surface quality of the panels would be the same, but the design would be ambiguous enough to place the panels anywhere on the façade without compromising the overall design.

After understanding and categorizing variability in the selected cases, fabrication methods for accommodating variability at the assembly level were studied.

2.2. Existing Fabrication Methods of Variable Facades

It has been observed by the authors that the number of panel variants on any façade with cast panels is typically low in order to reduce the need to fabricate multiple molds. However, some precasters have developed strategies to reduce the required number of molds. Among the studied built cases, there were two projects where variability was created by utilizing mold inserts. These projects include Le Vérone Building and the Perot Museum of Nature and Science fabricated by Techni Moulage and Gate Precast respectively.

Techni-Moulage is a small company based in France with a singular facility that produces mostly architectural precast objects. In this facility they fabricated the panels for the renovation of Le Vérone (Fig. 1), a building in Saint-Denis designed by Wilmotte & Associés Architectes for the online retailer Vente-Privee. The façade is composed of a fishnet pattern designed by Pucci de Rossi, an Italian artist and friend of the Vente-Privee CEO (Wilmotte & Associés, n.d.). In fabricating the 12 panel variants for the curved façade, Techni-Moulage used only a flat and a curved mold. To create the variations required, certain channels in the mold would be blocked off with reusable mold inserts, which minimized the need for more molds (Techni Moulage, n.d.).

Figure 1. Le Vérone Building Facade. Source: Photo by authors

The second project was the Perot Museum of Nature and Science. Gate Precast worked closely with Morphosis in conceptualizing a fabrication strategy to construct the façade for the Museum (Fig. 2). The intent of the façade design was to evoke geological striations, and included 656 panels with unique designs (Stephens, 2013). To fabricate those unique panels within budget, the team composed of both Morphosis and Gate Precast designers developed a mold system that utilizes interchangeable parts. These parts could be inserted into 4 differently shaped formworks to create 39 different geometries in the panel, either recessed or protrusions (American Institute of Architects, 2014) There were 12 different patterns, sometimes continuing from panel to panel, but when one views the façade the patterns seem completely random. Their advanced approach was different from traditional formwork construction, which allowed them to reduce the number of required molds during the fabrication process. Overall, the fabrication strategy of the design team was highly successful in creating variability for this project.

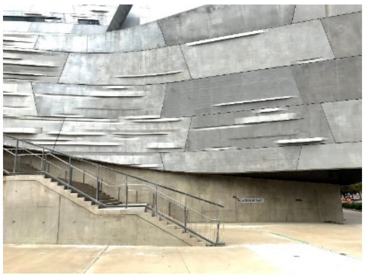

Figure 2. Perot Museum of Nature and Science Façade + Molds. Source: From *"Perot Museum Exterior Architecture"* [Photograph], by Jonathan Cutrer, 2017, Flickr (https://www.flickr.com/photos/joncutrer/37585013761). CC BY-SA 2.0;

The next sections describe in detail how Panels A and B were designed with inspiration from Le Vérone Building and Perot Museum of Nature and Science respectively. The former panel (panel A) prioritizes Design by conceptualizing a fabrication method that can accommodate a specific geometry. The latter panel (panel B) prioritizes Fabrication by exploiting design possibilities that the conceptualized fabrication method offers.

2.3. Panel A: From Design to Fabrication

Variability in facades can be designed with both a prescribed geometry, or with a prescribed fabrication technique. For panel A, the former approach was taken and the fishnet geometry of Le Vérone building was mimicked. Because the design aesthetics were prescribed, the major hurdle when designing the panel became organizing the geometry so it allows for the mold design to accommodate the digital fabrication of variability. Because of this, one must consider how to fabricate the panels at every step of design past conceptualization, and thus the new molding method was born very early into design exploration. To increase the variability of the panel in a controlled manner, it was found that the mold could be split into even segments that are both interchangeable and rotatable along the XY plane. This concept was applied to organize the geometry of Panel A by setting up the design with a 2x2 square grid. On all four sides of each individual square cells, 2 touchpoints were placed equidistant from the center of the square (Fig. 3). The geometry of the panels was developed around these guides, and with this controlled segmentation of the design the mold could be composed of 4 pieces that are all interchangeable and rotatable (Fig. 3).

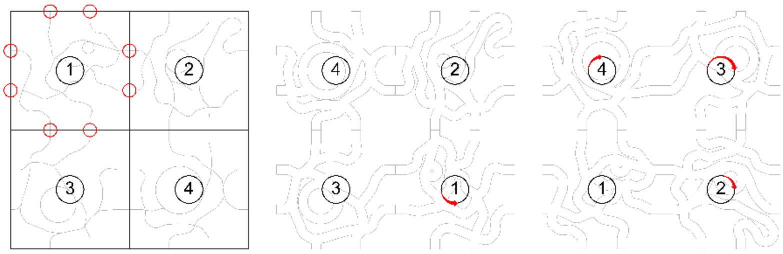

Figure 3. Initial organization of panel A (left) and two variants (middle and right). Source: Photo by authors

For digital fabrication of the mold, SLA desktop 3D printers were used. It was decided to utilize an elastic resin because the thin geometry of the panels likely required a flexible mold. The first iteration of the mold was unsuccessful in casting trials because the design was essentially just the thin geometry of the panels subtracted from a box. The large mass of the mold pieces prevented it from being very flexible, and thus prevented the cast object from being removed from the mold without a significant overpour. The design was revisited after being informed by a few other studies into thin-walled formwork (Naboni et al, 2018), and a thin-walled mold iteration was printed that was able to produce the delicate panels without breaking them during the demolding process (Fig. 4). However, when arranging the pieces in a tray the contact points between the thin-walled geometry were tricky to perfectly align and proved to be leaky. To prevent that, a number of clips were printed that could be placed at the contact points of the pieces to both align them and prevent leakage.

Figure 4. Picture of four 3D printed mold pieces placed in a tray. Source: Photo by authors

The experiments of designing and fabricating panel A with a prescribed geometry proved to be successful in that it limited the number of unique mold pieces to four, while the number of unique panel variants surpassed that. Although we did not experiment with creating panel variants using the same mold pieces inside a tray, this could also be done to further increase the possible number of unique panels.

Figure 5. Pictures of panel A variants. Source: Photo by authors

2.4. Panel B: From Fabrication to Design

For panel B the idea of interchangeable and rotatable mold pieces was expanded upon. The conception of the design started around the idea of using a square grid larger than the previously used 2x2 grid to organize the geometry. This time, however, the design of a particular connection point was completely avoided when arranging the 4x4 grid (Fig. 6). The panel's design developed to become ordered around 6 different inserts that vary in both the height and complexity of their top surfaces, but have the same length and width (Fig. 6). All but one insert have a doubly curved surface, and the heights along the upper edges of the inserts correspond with the height of one or two other inserts. The correspondence in height presents the opportunity to cast a panel with a complex and smooth surface. However, the correspondence in length and width present the inverse opportunity, the inserts may be moved interchangeably or rotated in the mold to create jagged edges. The opportunity to construct a façade that has patterns continuous from panel to panel becomes present with this design, similar to that of the Perot Museum of Nature and Science.

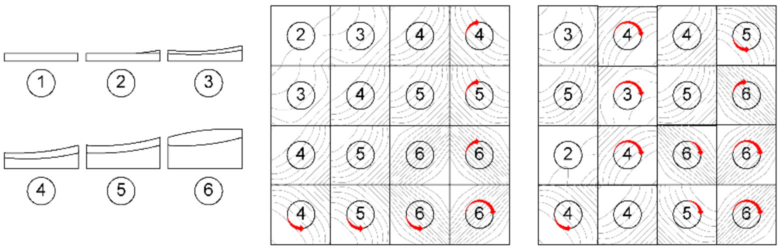

Figure 6. Elevation of panel B inserts and two variants with 0.5mm topological overlays. Source: Photo by authors

Because of the nature of mold B to act more as a form liner than a formwork it was decided to fabricate it out of clear resin, as less flexibility was required. The lack of flexibility of the mold pieces did, however, cause problems. We found that the thickness of the pieces needed to be a certain depth to be successfully removed from their printed supports. Otherwise, the brittle nature of the clear resin would cause the pieces to break from the force of the supports being removed. In the process of removing the supports, multiple of the thinnest pieces were shattered. Further, because of the difficulties removing the supports the pieces did not have even bottom surfaces. When casting, we elected to use a 3x3 grid of mold pieces instead of 4x4 as a result of the broken pieces. To allow for the top surfaces of the pieces to align when casting we elected to place them in a box of sand, thus eliminating the need for a finished bottom surface. An alternative approach could be to finish or reprint the bottom surfaces so that the pieces are level, which is likely a better option for quicker mold assembly (Fig. 7).

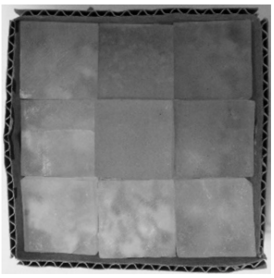

Figure 7. Picture of mold B. Source: Photo by authors

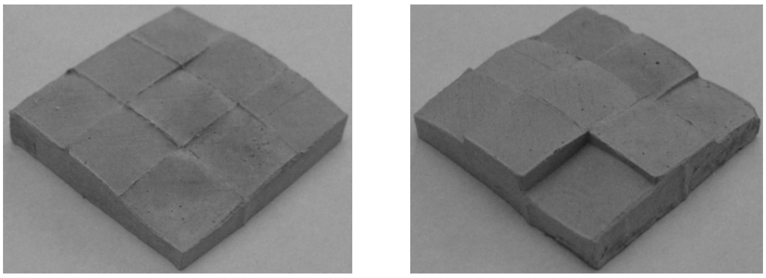

Figure 8. Pictures of panel B variants. Source: Photo by authors

3 Discussion

All design and fabrication was done in house with the use of Rhinocerous 3D and additive manufacturing respectively. Specifically, Rhino 6 was used to design the panels and Formlabs Form 2 SLA printers were used in the fabrication of the mold pieces. The mold pieces are made of multiple different resins that contain different mechanical properties. While the fabrication of reusable molds with additive manufacturing is a much less labor-intensive practice than the creation of traditional formworks, there were still hurdles that had to be cleared to successfully fabricate the molds. The problems encountered are unique to additive manufacturing, including the maneuvering of tolerances between pieces that must fit together and working with the material constraints of our chosen resins.

Both panels involved open molding techniques and CRM, but the form of Mold A acts more as a self-supporting formwork while Mold B acts as more of a traditional form liner. There was minimal labor involved in the fabrication of the molds through AM, which allowed for multiple mold pieces to be printed with minimal fabrication turnaround time. This meant that our mold design process turned into a cyclical and iterative process. There were failures in the first iterations of the molds, but we were able to quickly find them through casting trials and then go back and make changes to the design. This aspect of immediate feedback was extremely beneficial in developing the molding system for each project, and is only possible through AM and other forms of digital fabrication.

When printing a piece, 3D printers are usually unable to print the prescribed geometry of a CAD model to the exact dimensions present in the model. This is due to the inherent limitations of the additive printing process. For example, if a printer can only produce layers that are 1mm in depth, then the nominal dimensions of the printed object will be +/- 1mm from the CAD model. The ability of a printer to produce very thin layers and thus a more geometrically accurate print is called its resolution. Form 2 printers do maintain an extremely high layer resolution, with the lowest layer size being 50 microns and the max being 100 microns. The extremely high resolution of the printers did not eliminate the need to work around the tolerances of the prints. In particular, the fitting of clips for mold A proved to be a process that required multiple iterations before finding a tight fit.

The material constraints of the resins we used were discovered largely through print failures. Both the Elastic 50A Resin and Clear Resin developed by Formlabs were used. The mechanical differences between the two are primarily in their elasticity as the elastic resin has a much higher flexibility than the clear resin, which is solid and brittle (Formlabs, n.d.). However, the mechanical properties of the elastic resin made it much harder to print with. Oftentimes when using the elastic resin the 3D printer fails to cure a certain layer or section of resin enough, which disallows the next layer from properly forming and eventually causes the entire print to fail.

Although there were some challenges during the fabrication process, both mold designs are able to produce a number of panel variants from a singular mold. To perfect the casting process, however, more mold iterations are likely needed.

4. Conclusion

The lack of widespread variability in facades today can be partially attributed to the fact that cheaply and efficiently fabricating a large number of façade panel variants is difficult. After exploring the limitations of both modern precasting methods and those of digitally fabricated concrete, neither alone can meet the levels of varied output desired by contemporary designers. However, when paired together they can meet design and fabrication demands of both architects and precasters. The use of mold inserts inspired by observed traditional processes was paired with digital design and fabrication methods to create volumetric precast panels based on built contemporary designs. These newly developed variable mold inserts produced multiple panel variants from a singular mold. Further, BAAM practices for mold inserts in modern precasting methods reduce the cost per pour of producing architectural scale panels. If the proposed methods are paired with BAAM, the ability to economically produce a wide variety of volumetric façade panels becomes possible. However, the limits of this method are not yet fully understood. In the future, this study will further consider the principals of designing panels that offer variable assembly potentials. Other fields of study such as mathematics, specifically aperiodic tiling patterns, will be sources of knowledge for expanding the work.

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