Rapid Composite Formwork: An Automated and Customizable Process for Freeform Concrete Through Computational Design and Robotic Fabrication

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Abstract. This paper presents a series of case studies that incorporate industrial robotics and rapid prototyping tools in the fabrication of custom molds for pre-cast concrete construction. The research documents the fabrication of molds for customizable pre-cast concrete panels in non-standard shapes with unique surface textures. Materials including sand, expanded polystyrene (EPS) and poly-lactic acid (PLA) are employed to produce robust, reusable, and multiple component molds and inscribe custom surface textures through concrete casting. The fabrication workflows incorporate the limits and constraints of digital processes such as fused deposition modeling (FDM) and robotic hot wire cutting (RHWC). The application of FDM and RHWC to concrete formwork fabrication presents unparalleled opportunities to produce performance embedded prefabricated concrete. In the production of jointing conditions, reinforcing and support structures, and the embedding of conduits and insulating cavities, FDM of concrete formwork in PLA offers an integrated process for an interdisciplinary design and production of smart concrete forms. By combining the flexibility, precision, and speed of RHWC and FDM, this research demonstrates the capacity of this process to efficiently produce high-fidelity, intricate, complex and performance embedded geometries in concrete.

Keywords: Robotic fabrication · Hotwire foam cutting · 3D printing · Concrete casting · Rapid prototyping

1 Introduction

The advent of automation in architecture has provided opportunities for the design and production of increasingly complex assemblies fabricated using a variety of processes and materials and capable of simultaneously integrating multiple functions. The availability of a range of options in terms of production processes means that designers are required to apply as much consideration to the fabrication process as to the design outcome. Readily available customizable software plugins have allowed fabrication constraints to be incorporated within the design space, resulting in a new design paradigm which has been referred to as “Formation Embedded Design” [1]. The feedback loop created by design and production interaction has brought additional responsibilities for designers such as the need to incorporate the optimization of

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automated processes, material efficiencies, carbon intensity and life-cycle analysis as design constraints. Recently there has been a growing awareness of the need to apply CAD/CAM technologies to respond to environmental concerns. One area of particular interest to architects is the concrete industry. Concrete is the most widely used construction material in the world and its market demand is predicted to double in the next 30 years [2]. At the same time, the concrete industry is making efforts to reduce the carbon intensity of concrete as a construction material. As this market grows, there will be significant demand for innovation in concrete production that reduces the time, cost, and environmental impact of concrete construction.

Conventional concrete production that involves the use of standardized wooden formwork fails to unlock the full geometric potentials of concrete [2]. Recent work by the Block Research Group has sought to develop new techniques for the design and construction of topologically optimized thin concrete shell structures informed by the exploratory work of Felix Candela [3]. Novel approaches to fabrication such as fabric casting, pioneered by Spanish Architect Miguel Fisac have inspired the recent work of Andrew Kudless in his 'P-Wall' series [4]. Contemporary practitioners are applying new approaches to manufacturing which have afforded greater degrees of freedom and material control [5]. These approaches can be engaged in a manner that optimizes structural performance, limits waste and reduces the labor involved in the construction of elaborate formwork while at the same time unlocking concrete's formal and aesthetic capacities. Integrated design processes which incorporate performance optimization, automated production and composite material assemblies allow designers to embed performance attributes and use materials more resourcefully [6]. While these technologies are often discussed regarding their efficiencies, they also offer designers more opportunities for generating emergent material effects and ornamental designs combining materialization and formation logics [7]. This paper therefore focuses on a combination of design and fabrication methods which leverage digital techniques towards material efficient and performance embedded concrete prototypes that feature unique surface textures. This study is part of an ongoing body of research undertaken by the Laboratory for Integrative Design into material, form, pattern and automated production techniques.

2 Digital Formwork

The digital fabrication of molds for mass-customized concrete components involves multiple constraints such as the inherent material properties, limits of tool positioning, and production costs. In response to these challenges, the production of concrete molds often involves methods that can quickly produce lightweight shapes using cheap and reusable materials.

Robotic hot wire cutting (RHWC) of expanded polystyrene (EPS) is one such approach that enables designers to cut through large volumes at significantly lower processing times, while resulting in highly smooth and low-cost molds [5]. EPS is inexpensive, recyclable, easy to shape [8], and its lightweight properties allow for the development of larger volumes that are easier and quicker to construct [9]. Furthermore, when compared to computer-numeric-controlled (CNC) milling, RHWC is faster, more cost-effective, and uses less energy during manufacturing. RHWC is also considered to be a less wasteful process, since it produces offcuts that can be reused for future cutting or as packaging for safe transportation rather than shredded down or dusted foam particles [9].

Another digital method that can produce lightweight concrete molds relatively quickly using cost-effective and reusable materials is known as fused deposition modeling (FDM). FDM can employ a wide variety of plastic materials that range in properties - biodegradable, fiber-reinforced, water soluble, flexible, etc. [2]. PLA is a relatively common material used in FDM due to its versatility, low shrinkage factor, and ability to be infinitely recycled or composted [2]. The main interest in using this method in the production of concrete molds is the expectation of new freedom in terms of design geometry as well as new aesthetic and functional features. Moreover, FDM can be used to produce thin, rigid geometry for lightweight formwork, and its precision can reach one tenth of a millimeter [2].

Both EPS foam and PLA can have a second life after being used as concrete molds. EPS can be broken down, melted, and re-molded through a closed-cell process [10], or it can be mechanically broken down into small 3–5 mm pieces to be incorporated into concrete mixes for a lightweight concrete panel [11]. Likewise, PLA can be recycled into new 3D prints as it is easy to clean, and it can be shredded back into pellets for extrusion in new 3D prints [12]. In addition, being made of biodegradable materials, PLA can alternatively be composted [13].

The case studies in this paper thus investigate the applications of robotic procedures and FDM using cost-effective and easily recyclable materials such as EPS and PLA in order to address the growing trends in innovative concrete mold production. Each study aims to balance performance attributes with emergent aesthetic qualities, while demonstrating the capacity for digital technologies to offer flexibility, precision, speed in the fabrication of unique concrete molds.

3 Case Studies

In this section three case studies are presented that have been part of an ongoing research investigation at the Laboratory for Integrative Design at the University of Calgary. The investigations explore the automated processes, material efficiency, and aesthetic expression in the production of concrete molds.

3.1 Bookmatched Panels

The first case study explores how composite concrete molds can be produced through a combination of RHWC and FDM processes. These processes were applied to create a vocabulary of formal and surface effects through an iterative process of digital and physical exploration. A series of highly articulated surface geometries were created by cutting EPS foam with multiple overlaid ruled surfaces which consist of infinite straight lines [16]. The resultant articulations were then trimmed into standardized panel sizes.

This process allows for both sides of the cut stock to be utilized, producing mirrored, or "bookmatched" surface effects. Custom 3D printed PLA frames were designed to clamp around the EPS surface forms and allow for easy release so that the surface panels and frames could be interchanged and reused. This method resulted in the rapid production of low cost and reusable molds that could produce highly intricate concrete forms with a high degree of geometric freedom (Fig. 1 and 2).

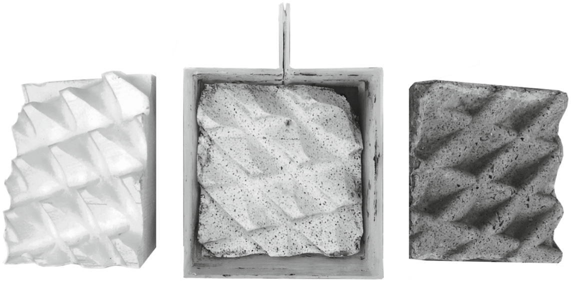

Fig. 1. Assembly of EPS foam texture and PLA 3D print into concrete formwork

Fig. 2. Samples of concrete casting using RHWC textured EPS foam and PLA formworks

The robot mounted hotwire cutter was custom made to be adjustable using T-slot aluminum extrusions that could be reconfigured to adapt to different scales. As well, the cutter was fit with an adjustable power supply to vary voltage and amperage through a nichrome wire tensioned across the frame. The custom cutter was mounted to an ABB IRB 2600 robot with a flat plate that could be easily bolted on (Fig. 3).

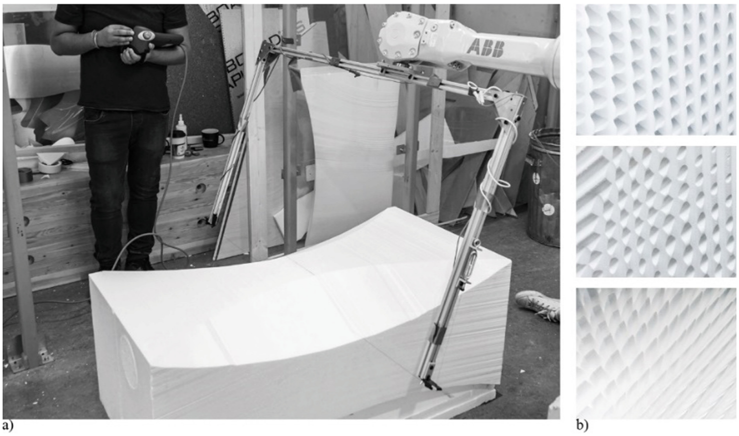

Fig. 3. a) Custom built adjustable T-slot robot mounted hot-wire cutter b) various lighting and textural effects from different cut angles and frequency

Ruled surface toolpaths were generated and simulated using the TACO [14] plugin for Grasshopper 3D [15]. Within this parametric environment, constraints such as tool rotation, the frequency and amplitude of toolpath, approach and retraction vectors, and speed were parameterized to develop toolpaths with consistent kerf (Fig. 4). The toolpaths were simulated to check for collisions and out-of-reach errors. By incorporating these constraints, the toolpaths could be adjusted without time consuming physical tests, extra material waste, or damage to equipment. This also allowed for the optimization of robotic movements to prevent sudden accelerations, stops or joint re-orientations that would result in excessive melting or dragging of the hotwire through the foam. By iteratively developing toolpaths in a constraint-based modeling environment, increasingly complex and readily fabricable geometries were designed and tested before moving into production.

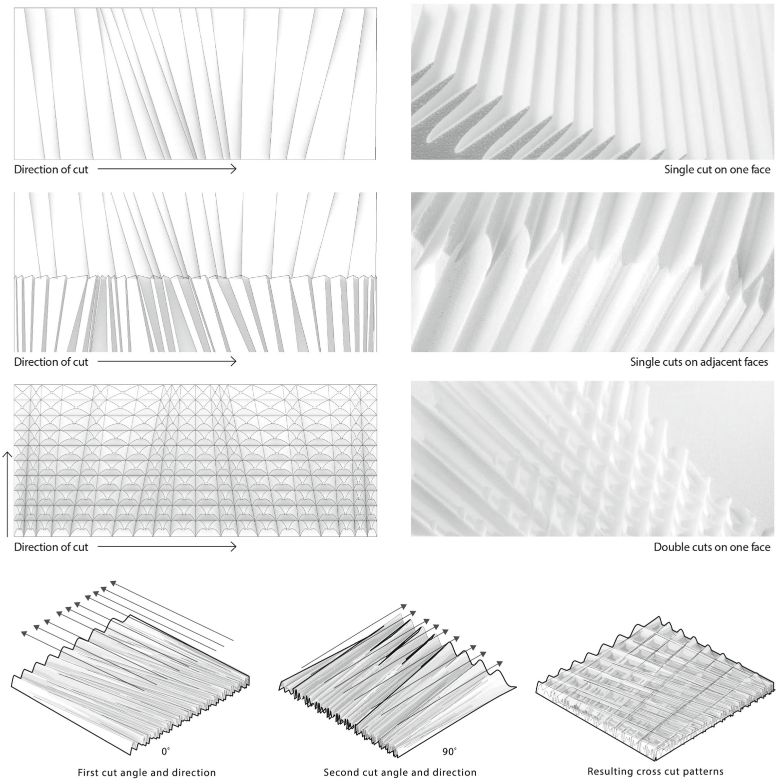

Fig. 4. Increasing complexity of surface patterns with additional and overlapping cut direction at various heights and angles

The 3D printed perimeter frame was printed on a Delta WASP 3MT printer using PLA pellets. The printer features a 1 m^3 build volume and can achieve a layer height of approximately 1 mm and a wall thickness of approximately 5 mm, allowing for prototyping at a construction scale. The 3D printed standardized frames were designed to hold the textured foam surface panels and to be tightened using hand clamps to remove gaps between the wall of the 3D print and the foam. This configuration allowed for easy release of cast prototypes while providing adequate strength to resist hydrostatic pressure and wear and tear from repeated use.

The composite mold fabrication techniques described in these case studies have the potential to reduce material waste and improve the potential recyclability of mold components when compared with standard custom concrete mold making techniques. We propose that composite EPS and PLA molds fabricated using RHWC and FDM printing provide a range of opportunities in terms of aesthetic expression and geometric freedom while at the same time providing benefits in terms of material efficiency and performance optimization. Further, we propose that this system could be tuned to respond to a wide range of aesthetic and functional parameters.

3.2 Volumetric Hotwire Cut Formwork

The second case study builds upon these RHWC techniques for creating articulated surface conditions by investigating how they can be applied to the development of volumetric concrete panel molds to produce architectural elements such as columns, arches and vaults with embedded performance qualities. In this case, ruled surface cuts were mapped onto cylindrical volumes and converted into toolpaths which exploited the range of motion available to a 6-axis robotic arm. The surface patterns resulting from these toolpaths incorporated parameters such as the size and depth of a foam block, amplitude, wavelength and frequency, rotation angle of the tool, and the height at which the robot arm started and finished the cuts (Fig. 5). This exploration aimed at exploiting the degrees of freedom and reachability of the hot wire cutter in order to optimize the cutting of volumetric geometries.

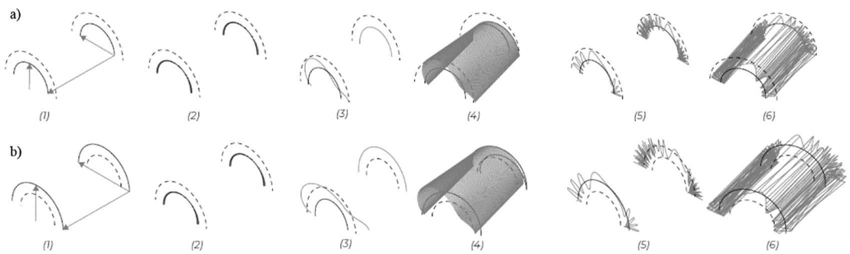

Fig. 5. a) Simulation along the inner curve b) Simulation along the inner curve 1. Defined cut parameters 2. Variable density along the curve 3. Smooth NURBS curve defined using variable amplitude and wavelength 4. Lofted curves to create ruled surfaces 5. High density NURBS curve defined 6. Ruled surface toolpaths for hotwire cutter

This study builds on the formal surface articulation vocabulary developed in the initial case study and extends this investigation by exploring combinations of surface patterns and volumetric geometry. At the same time, it points to the potential for further research into the integration of additional functions within the formal language. For instance, the composite mold technique could be manipulated to embed spatial requirements for metal frame reinforcement or 3D printed cores for carrying services through the columns. Figure 6 demonstrates this capability and exemplifies an instance where intricate geometry is achieved externally while the internal condition is simplified to easily accommodate a steel frame. This aspect raises questions of expanding the aesthetic catalogue towards realizing a range of technical facilities related to heat exposure, acoustics and thermal performance.

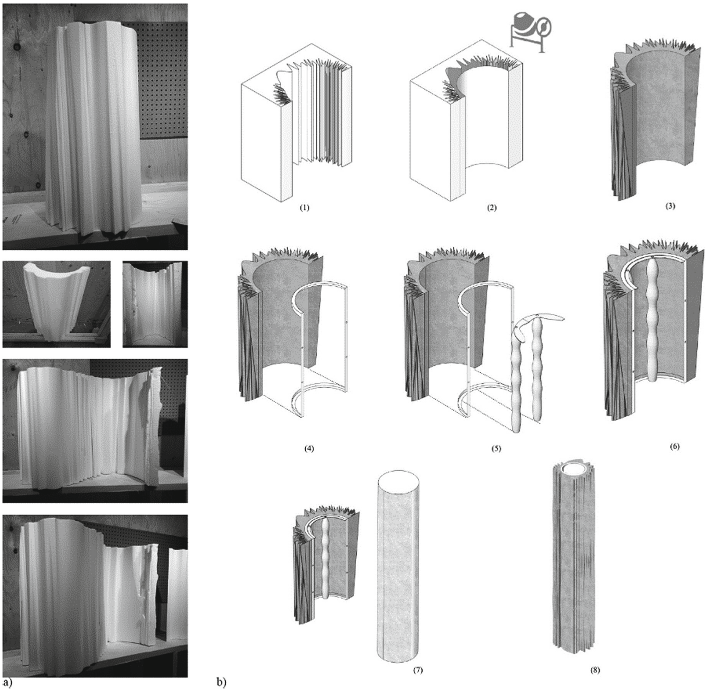

Fig. 6. a) Iterations of volumetric foam cuts and off-cuts b) 1. Existing off-cut foam mold 2. Concrete casting 3. Casted piece 4. Metal framework attached to casted piece 5. 3D printed core for carrying services 6. Single module with attachment and service cores 7. Attachment of module to existing column 8. Panelization of module

3.3 Penrose Panels

The third case study investigates a robotic fabrication procedure that utilizes reusable, modularized molds in the production of bespoke concrete façade panels. Initiated by an interest in balancing waste reduction strategies with customized aesthetics, the study employed FDM using recycled PLA to create lightweight and standardized mold containers to host loose sand for a robotic arm to draw unique patterns into. In this system, flexibility could occur at the level of the sand, while the mold containers remain constant and could be reused for new sand patterns. The process constantly moved between digital and physical space - digital data defined the mold outputs and robotic movement, and material and spatial data modified the toolpathing sequences. This system also enabled jointing functions to be designed and embedded into the concrete casting process so that the unique panels could be assembled with ease. The investigation used the Penrose (1974) fractal pattern to abstract an image into subdivisions of rhomboids, which also defined mold geometry from the two rhombic figures that the pattern operates with (Fig. 7).

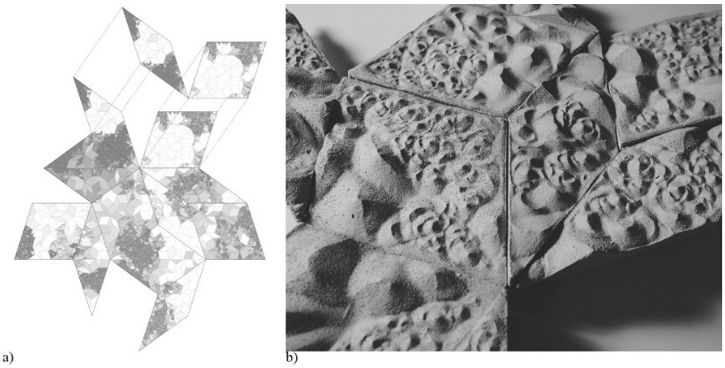

Fig. 7. a) Image abstracted using Penrose fractal subdivisions b) Concrete Penrose Panels

The recycled PLA mold containers were designed to fit into 0.2 m $\times$ 0.2 m laser-cut plywood bases and be clamped together to contain the loose sand (Fig. 8). The sand would then offer an adaptable platform for a UR10e robotic arm to draw into using a variety of 3D printed and laser-cut toolbits held by a RobotiQ gripper. Of the many different sequences that were developed to translate the patterns into robotic toolpaths, one sequence was chosen to produce all 11 panels since it better leveraged sand's inclination to fall into peaks and valleys around the moving tool (Fig. 9). As a result of the indeterminacy of the material, the workflow formed a feedback loop in which the material characteristics dictated the scale of the Penrose subdivisions, as well as the toolpath angles, depths, and speed.

Fig. 8. 3D printed recycled PLA and laser-cut plywood mold containers

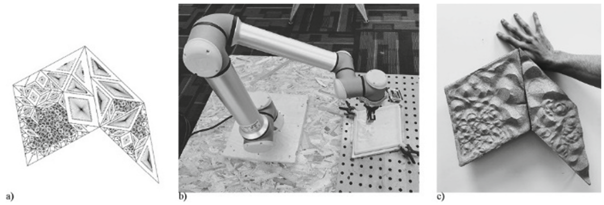

Fig. 9. a) Toolpathing data b) Robotic execution in sand c) Resultant concrete panels

Once the robotic toolpathing was completed, the molds were sprayed with liquid latex to solidify the sand and create a smooth, releasable layer for the concrete to be cast upon (Fig. 10). Laser-cut plywood jigs were also produced to fit on top of the molds so that bolts could be casted into the back of the concrete in locations that corresponded to a universal connection piece – the panels' edges all shared a common angle that was revolved to create a connecting wheel (Fig. 11). Once the concrete was set, the molds were deconstructed, the latex was peeled off, and the sand and mold containers were reused to create more custom panels.

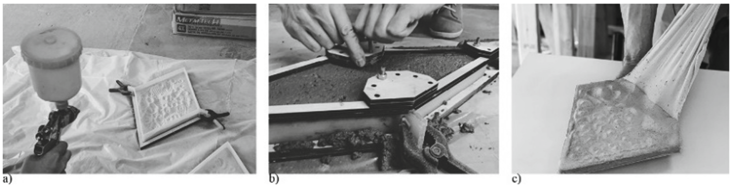

Fig. 10. a) Latex spraying b) Bolt-embedded concrete casting c) Latex removal

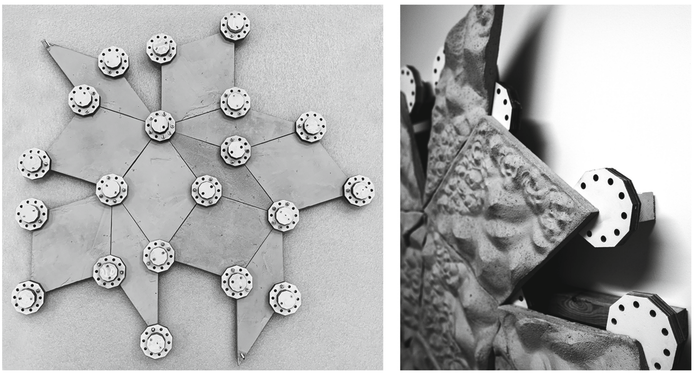

Fig. 11. Universal joint connection wheel on panels

The flexible nature of the sand patterning suggests that further performance attributes could be integrated into the concrete formwork such as solar analyses or acoustic data, and the robotic procedure could potentially produce areas for aperture in the panels.

4 Conclusion

This paper has presented a series of studies that aim to explore how designers can meet the freedom afforded by automated technologies with responsible design intentions that engage critical contemporary issues. Each study has demonstrated ways in which limits and constraints associated with automated fabrication methods can inform integrated and feedback-based workflows for producing complex concrete formwork. Furthermore, various strategies for reducing embodied carbon such as material optimization, recycling, and reuse have also been showcased in the studies, and the use of industrial robotics has been highlighted for their ability to offer designers a platform for developing customized, material-focused, and performance integrated formwork designs.

It should be noted that there are limitations on the ability of FDM printed molds to resist the hydrostatic pressure imposed by higher casting heights. While this limitation is somewhat mitigated by using a large format FDM printer with a larger nozzle diameter and higher wall thicknesses, the actual limitations on casting height using this technique remains to be tested. We have started to investigate some potential methods for addressing these limitations, including: the discretization (subdividing into separate parts [17]) of the formwork, as well as the introduction of additional support elements such as bracing or the use of sand to support the molds [17], or by controlling the concrete hydration and rheology parameters via the inclusion of additives for the optimization of concrete for 3D concrete printing [20] or slip-casting [21] within the concrete mix.

Aside from further exploring highly articulated aesthetic expressions, the flexible nature of these systems could unlock many more opportunities for deploying new datasets or integrated services into concrete formwork formation and materialization. Further research will continue to explore how these approaches can be deployed at larger scales and optimized to incorporate additional functionality in order to integrate performance and aesthetics in a more sustainable approach to composite concrete formwork.

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