FABRICATION OF ULTRA-LIGHTWEIGHT PARAMETRIC GLASS FIBER REINFORCED SHELL ASSEMBLIES

JONATHAN MING-EN NG¹, SAMUEL YU DE HO², TRUMAN WEI CHENG NG³, JIA YING SOH⁴ and STYLIANOS DRITSAS⁵
¹,²,³,⁴ Singapore University of Technology and Design
¹,²,³,⁴ jonathan_ng|samuel_ho|truman_ng|jiaying_soh}@mymail.sutd.edu.sg
⁵ stylianosdritsas@sutd.edu.sg

Abstract. We present an experimental form-finding technique for ultra-thin glass fiber reinforced concrete components and assemblies. The objective is to challenge conventional concrete use in construction, often perceived as a massive and compressive structural material. Instead, we targeted production of fine shell assemblies principally operating in tension. To achieve thin profile components, we use a compliant molding technique where premixed GFRC is cast in polyethylene bags. Subsequently, a robotic arm system pins the bags on a substrate plate and the setup is inverted whereby gravity induces a curvature to components while concrete cures. Use of parametric modeling, computer simulation and statistical experimental methods allowed us to understand the behavior of the material process and translate computationally modeled designs into physical artifacts. We discuss the opportunity for digital fabrication methods to fuse with traditional form-finding techniques, contrast the use of computational modeling techniques and present a series of prototypes created through our process.

Keywords. Digital Fabrication; Glass Fibre Reinforced Concrete; Form-Finding.

1. Introduction

Concrete is a composite material widely used in architecture and general construction for its low-cost and considerable structural strength in compression. Its mechanical weakness in tension is alleviated by inclusion of reinforcement, most often in the form of steel rebar or technical fibers. Nevertheless, its use in architectural design pivots about its excellent compressive characteristics so much so that concrete is almost synonymous with compressive structures. In addition, concrete is also associated with casting fabrication techniques, a result of the exothermic reaction of hydration transforming the composite material from liquid to solid state. Casting concrete is a wet construction process, typically laborious due to requirement for mold fabrication; and generally considered inaccurate, because often it is performed on site under uncontrolled environmental conditions.
conditions. Despite this limitation, concrete is one of the very few materials used in construction that can produce fluid and continuous solid geometries exactly because of its unique material and fabrication characteristics.

The broader domain within this work is situated in digital fabrication. Its aim is to investigate how programmable methods of production, such as computer numerical control and robotic machinery, can assist creatively to develop new methods for materializing architecture and/or improve aspects of current construction methods. Our work explores creative applications of concrete fabrication, within digital fabrication, starting from challenging its predominant use as a compressive material, which is often also coupled with geometrically massive and heavy-weight artifacts. Instead, we aimed at creating thin-profile elements, assemblies thereof primarily working in tension (Figure 1).

Figure 1. Ultra-thin glass fibre reinforced concrete element with white cement.

2. Background

Use of concrete for tensile applications has been investigated extensively in the past with indicative built precedents including Le Corbusier (Expo ‘58 Philips Pavilion, Brussels, Belgium 1958), Kenzo Tange (Yoyogi National Gymnasium, Tokyo, Japan 1964), Alvaro Siza Vieira (Expo ’98 Portuguese National Pavilion, Lisbon, Portugal 1998). Thin-profile concrete became feasible by the introduction of reinforcing fibers such as typically glass and carbon, with diameters in the range of microns as opposed to conventional steel in the range of millimeters. Architectural applications of glass fibre reinforced concrete are mainly in building envelopes such as the Heydar Aliyev Center (Zaha Hadid Architects, Baku, Azerbaijan 2012) and the Broad Museum (Diller Scofidio + Renfro, Los Angeles, California, USA 2015). Conventional concrete is typically cast in timber and metal and formworks for columns, beams and slabs, where substantial hydrostatic pressure is accumulated while the material is wet, while panels are often molded using foam and silicone formworks. Research for concrete fabrication is centered about additive manufacturing (Khoshnevis, 1998, 2004; Lim et al, 2012; Bos et al, 2016) which alleviates the need for mold making but introduces challenges for reinforcement embedding. Computer numerical control (CNC) milling techniques have been used for free-form mold fabrication (Gramazio and Kohler, 2009; Sondergaard and Dombreowski, 2011; Peters et al 2016), additive manufacturing techniques for mold making (Hack et al 2014; Gardiner and Janssen, 2014;
Gramazio and Kohler, 2017) as well as a flexible moulding (Loretto Kristensen, 2014) and casting methods (Lindemann et al, 2016). Form-finding techniques for concrete fabrication often use compliant molds to allow for material-force interactions to give rise to geometry. Relevant work includes use of fabric molds for concrete casting (West, 2003; West and Araya, 2009; Veenendaal D. and Block P, 2014), use of soft plastic membranes for casting (Kudless, 2011), robotic fabrication with fabric casting (Culver, 2016), thermoformed mold fabrication for casting (Tian et al, 2017).

3. Material Techniques

Achieving double-sided high-surface-finish thin-wall concrete parts often requires two-part molds where concrete is injected in the cavity. However, the thinner the wall, the more difficult the process becomes as concrete, a generally viscous composite, needs to flow and fill the cavity uniformly. If only one surface needs to exhibit high-surface-finish, premixed concrete with fiber reinforcement is sprayed directly onto the exterior surface of the mould and the back face is manually rolled and compacted. Typical thicknesses for GFRC panels are in the range of 12 to 25 $\text{mm}$ (Glassfibre Reinforced Concrete Association, 2017; Glass Reinforced Concrete Ltd, 2015; Telling Ltd, 2018). With concrete density circa 2,000 $\text{kg/m}^3$, at typical 20 mm thickness, a GFRC panel weight approximately 40 $\text{kg/m}^2$. The process developed aimed at (a) eliminating the need for creating multiple varied moulds for producing parametrically designed artifacts, (b) achieve comparable surface finish results with highly polished moulds, and (c) reduce component weight substantially, ie. producing 2-4 $\text{mm}$ shells with approximate weight of 5 $\text{kg/m}^2$, for enabling tensile concrete design and fabrication.

3.1. CONFORMAL CASTING

The method developed uses low density polyethylene (LDPE) films between which premixed GFRC is poured, followed immediately by pin rolling to conform its thickness and compact the composite. As the chemical reaction of cement hydration is governed by water content, rather than oxygen, concrete cures even if enclosed in sealed bags. After the thin-sheets of cement begin to harden, but before fully cured, there is a window where they can be formed while retaining approximately constant thickness. Their surface finish is directly transferred from...
the plastic material which if left flat against a hard surface results into high-polish like parts, if the plastic is wrinkled it is possible to produce high-resolution textured artifacts and if softly deformed can result in parts with smooth surface and curvature characteristics. Initial experiments using plastic wrap films with thickness circa 10\(\mu m\) produced extremely high-resolution textures. Later, to simplify production we used ziploc bags with thicker walls circa 50\(\mu m\) which resulted to reduced surface texturing and smoother finish. Additional benefit of closed bag conformal casting included the control of part edge condition which for open double layer membranes required edge stamping to enforce boundary geometry and inducing predicted failure points for trimming after curing (Figure 2).

![Figure 3. Above: Casting thin-shells using LPDE membranes. Below: Experimental results of shells.](image)

Differentiating characteristics of the process are in its rapid production of thin shells using recyclable bags, with smoother finish than woven fabric moulds and with the ability for in-process application of deformation operations. We performed a series of experiments for understanding the range of options available for component forming including draping the molds over rigid surfaces, performing deformation operations such as twisting or folding the bags and hanging them, letting gravity give shape to parts. Experimental prototypes exhibited unique and unexpected characteristics for concrete such as the intense fabric-like wrinkling and geometry pleating and high fidelity texturing (Figure 3). From those, hanging bagged concrete produced geometries that required no additional objects to conform against and smooth double-curved geometries with form-finding characteristics, produced efficiently. We therefore proceeded with the later approach and towards resolving part-assembly challenges. Being able to create parts with ultra-lightweight properties and sufficiently strong in tension to support one another due to the glass reinforcement, guided the design direction towards pinning components together into hanging assemblies. Linkage penetrations were introduced by puncturing the bags with a nail gun against a foam surface before inverting and letting cure. Thereafter, the penetrations were used for connecting parts with one another.
3.2. MATERIAL CONFIGURATION
The ratio between water and cement is critical for the strength of cured concrete as well as an important process parameter for molding. Additionally, introducing even small amounts of glass fiber causes significant increases in its viscosity. The objective of evaluating various water-to-cement and glass ratios was to find an operating point where the bagged material retains its approximate thickness during forming. If too much water is used then the material flows too easily between the membranes, concentrates at the lowest points of the mold and weakens the boundary fixture points. Excessive water content results in the inability of the concrete mixture to hold the glass-fiber strands apart during mixing, causing undesired clumps of glass-fiber which later leads to uneven strengthening of the shell. If too little water is used then rolling the preform becomes more difficult and during forming the point of highest curvature tend to crack. The process of mixing is also critical because if too much air is introduced in the material then air bubbles appear on component surfaces. After a series of experiments we concluded that 2:1 water to cement with 1% glass was sufficient for producing pliable and sufficiently strong components.

3.3. DIGITAL FABRICATION
The overall fabrication process involves multiple steps including: (a) premix preparation of glass fiber reinforced concrete, (b) dispensing material in bags and rolling preforms flat and to constant thickness, (c) fixing two corner points of the rectangular bag against a foam board, (d) displacing the third before fixing it in place, (e) flipping the part to take shape and racking till cured. From those, the most critical operation for achieving controllable design objectives is the process of deforming the bagged mold. We developed a digital fabrication method using an industrial robotic unit equipped with a pneumatic nail gun end-effector (Figure 4). The robot driven by a parametric Computer Aided Design model performs the operation of locating the two stationary points registered against a fixed external frame against its coordinate basis and displacing the concrete bag by shifting its third corner to a desired location before fixing its position. Once the foam board is flipped, the fourth point of the bag deflects by gravity, inducing shape to the part. Material dispensing and machine tending are performed manually but those are easier process tasks that can be automated given additional robots. Control of the motion profile and association between the location of the three fixed and fourth floating point in relationship with the resulting part shapes was something difficult and worthy of approaching computationally. The robotic setup affords several benefits in this respect, such as scalability for complex geometries, more fixed points and variable bag sizes as well as consistency across scales and production volumes.
3.4. PARAMETRIC MODELING

To begin understanding the material process behaviour such that we could design the large assembly of form-found components and drive the robot towards desired directions, we developed a series of computational models. Their objective was to predict the general shape of each component to enable design of a parametrically varied assembly with controllable surface openings. Three points fixed in-plane and the fourth let free, produces catenoid-like surfaces for which we aimed to predict their vertical deflection.

The simplest model developed was based on parametric geometry of a square bi-fold with side \( r \), where two planar triangles are rigidly transformed by decreasing their included planar angle \( \alpha \) driving the apex point vertically off the plane by \( h \) (Equation 1). While this model was simple and effective it missed the curvature characteristics of the parts.

\[
h = \sqrt{\frac{r^2}{2} - r \sqrt{1 - \tan^2(\alpha/2)}}
\]  

We thus developed a simulation model by approximating the planar sheet with a 4 by 4 grid of edges, including internal tile diagonals, using springs and letting gravity deflect the model. To achieve faithful approximation of the physical behaviour, we had to preset the spring rest-lengths and use three orders of magnitude higher stiffness to gravity factor. The model performed well, including picking up the potential of wrinkles across the transverse folding diagonal. Nevertheless, it required circa 4,000 iterations to converge, which was rather slow.

We thus created a simplified model that aimed to approximate the catenary shape across the transverse fold diagonal. This is a parameter estimation problem where the length of curve is known \( l \) and distance between the support points \( s \) but not the catenary scaling factor \( f \) (Equation 2). It can be efficiently solved using numerical methods within a few iterations; here we used the Brent solver.
converging in typically 10-12 updates. This gave as good results of deflection as the simulation model in microseconds.

\[ l = 2fs \sinh(s/2f) \]  

(2)

Despite the efficiency of the analytical approximation models, we suspected that the interaction between the material and compliant mold process was not fully captured. We thus approached predictive modeling of the deformation problem using an experimental design model including the material water-to-cement ratio \( w \), presence of glass reinforcement \( g \) and robot angle motion \( t \) as driving parameters, where \( w, g, t \in [-1, 1] \) and measured the geometric features of produced parts such as included angle \( a \), vertical deflection \( h \) and elevation angle \( b \) (Equation 3-5). Analysis of the regression results showed the effect on the geometry was dominated by the robot motion rendering all other factors and interactions insignificant. Interestingly while the generated models are linear they do embed inherent inaccuracies due to setup, preform flattening and material interactions which analytical models ignored, they are simple to derive and apply.

\[ a = 63.697 + 0.079w - 0.174g + 19.429t - 0.013wg + 0.236gt + 0.630tw - 0.079wgt \]  

(3)

\[ h = 126.591 + 0.380w + 0.595g - 39.263t - 0.814wg + 1.109gt - 1.746tw - 0.906wgt \]  

(4)

\[ b = 27.991 - 0.235w + 0.093g - 9.448t - 0.154wg + 0.302gt - 0.513tw - 0.247wgt \]  

(5)

Figure 5. (top to bottom) Geometry model, Simulation model, Catenary model, Experimental model.
4. Prototyping

Beyond numerous single panel prototypes produced for assessing the ability to create predictable results, we developed a larger prototype aiming to assemble multiple parts into a tensile configuration. The design is comprised of 40 varied tiles in a cylindrical diagrid shingle arrangement with overall dimensions of 0.8 m in diameter and circa 0.9 m vertically. Each row is progressively deformed resulting in a gradient aperture opening envelope. Each shingle measures 200 by 200 mm in plane and preform thickness of approximately 3.5 mm while after forming their shape has acquired a depth of between 75 and 165 mm measured between the plane defined by the fixed points and the fourth projection. The weight of a shingle is approximately 0.25 kg, totaling up to 10 kg. Shingles are connected using plastic line to allow by flexure to absorb fabrication tolerances and are horizontally strapped with compression rings per row to induce vertical curvature and reduce node-to-node jointing complexity and risk for edge fracture. Overall, the prototype’s appearance is symmetric which shows certain level of process variability control. Their edges are highly defined coming to a knife-point. Due to inadequate compaction however, there is significant amount of surface porosity due to air bubble formation. Use of white cement and plastic bag mould resulted in highly reflective and pleated tiles with low thickness, which upon cursory inspection is completely unclear what material was used or how the artifact was created.

Figure 6. Assembled prototype with tile finish detail.

5. Conclusions

We presented a digital design and fabrication process using LDPE bagging for GFRC molding. The method can produce ultra-lightweight components with
unique surface and geometry characteristics. Envisaged applications for this method are in rainscreens and general cladding as well as public artwork, the larger prototype development targeted. A question arising from the development of this technique pertains its scaling ability to produce much larger scale artifacts than small scale tiles assembled in larger configurations. In as much as fabric formworks have been successfully used in the past for larger scale architectural component fabrication, it is foreseeable that use of plastic membranes offers an equivalent technique, with its own unique characteristics. Process parameters such as membrane thickness would have to then significantly increase to sustain the weight of concrete and consequently the range of curvature and surface texture definition reduce. As building geometries generally feature subtle or locally simple curvatures, the use of bagging technique could present an efficient method for GFRC panel fabrication which does not require individual mold production. While we took a rather extreme approach in terms of both the part thickness as well as suspension method, with more conservative thicknesses and fixture strategy avoiding surface penetrations, it may be possible to reuse the same jig-mold to produce a wide variety of curved geometries. We believe efficient fabrication processes characterised by minimal material use offer the opportunities to create unique designs with low resource impact.

![Figure 7. Prototype installed with interior light.](image)

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