PolyBrick: Variegated Additive Ceramic Component Manufacturing (ACCM)

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Abstract

This article showcases the next steps in the integration of complex phenomena towards the design, production, and digital fabrication of ceramic form in the design arts and architecture. This work includes advances in digital technology, three-dimensional (3D) printing, advanced geometry, and material practices in arts, crafts, and design disciplines. PolyBrick: Variegated Additive Ceramic Component Manufacturing (ACCM) documents the use of algorithmic design techniques for the digital fabrication and production of nonstandard ceramic brick components for the mortarless assembly and installation of the first fully 3D-printed and fired ceramic brick wall. Techniques in parametric and associative environments are incorporated with feedback derived from material constraints as well as performance assessments. Using customized digital tools, low-cost printing materials, and component-based aggregations, our research utilizes readily available 3D printing technology to develop large-scale forms through the aggregation of interlocking component based systems. Operating within the scalar limitations of current print bed sizes, we developed and tested a set of mass-customized components with embedded local and global awareness and demonstrated that we could achieve forms much larger than previously possible. We have effectively designed a system for mortarless brick assemblies at scales beyond existing constraints of the print bed size of a large-format color printer.

Introduction and Background

The production of ceramic blocks and tiles has a vast technological and design history. Ceramic modules of standard measurement have been used as a building block and replacement of stone for centuries. Contemporary interest in the ceramic module and technical advancements in prefabrication have offered prefabricated non–load-bearing brick façades.[1] Surprisingly, ceramic bricks and tiles, so ubiquitous in their application in the built environment, have lacked recognition as a viable building component in contemporary architecture practice until now. Industrial and technological advances have shown us that ceramic production can be manual, mechanical, and now digital. The use of CAD/CAM technologies to automate the design and fabrication of ceramic forms has since inspired a new appreciation for ceramic material in architecture, but further design research and production is necessary. Importantly, the plastic nature of clay offers a potent material solution to contemporary generative design processes in architecture, which frequently feature organic and natural forms of increasingly complex expression and ornamentation.

Clay: A Practical Medium for Negotiating Complexity in Design

The use of clay in the design process to rationalize complex data and geometries has been incorporated in other industries such as car and boat design for decades. While the car industry has significantly advanced the design of digital tools and CAD/CAM processes, clay modeling is still one of the most traditional and reliable methods used in the design of cars. Modelers may work from existing digital drawings through the precise transfer of contours, or they may sculpt and form the clay by hand early in the form-finding process. Once

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this process is complete, the clay concept car will be 3D scanned to produce a 3D digital wireframe. Typically, this model will be finessed in a digital modeling environment to smooth over inconsistencies before being passed to engineers for component design and panel production.[2] This process presents a very interesting transfer of information and data through the hybridization of crafts-based techniques with contemporary digital design. In contrast to what is being done in the area of car design, very few technological advances have been made to hybridize the ceramic building block to achieve variable and complex curvatures and surface strategies. The time-consuming nature of the manual molding of clay has inspired technological advances, both mechanical and digital, with the intent of increasing the speed of execution and control of the highly dynamic nature of clay. However, very little has been done to bridge digital processes with the production and design of nonstandard ceramic building blocks in architecture, especially in the area of direct 3D-printed clay bricks. Given its structural and material capabilities alongside contemporary advancements in 3D printing, the PolyBrick project presents a series of intricate tectonic and material methodologies with scalable applications in architecture.

There are several research units advancing existing traditional methods for brick production, such as extrusion, through advances in robotic fabrication. For example, the Design Robotics Group at the Graduate School of Design at Harvard, led by Martin Bechthold, is using robotic fabrication for the production of complex ceramic systems.[3] They have incorporated wire-cutting, an age-old technique for shaping clay, as an addition to a robotic arm, thereby creating nonstandard clay modules that interlock and nest with their neighbors for larger aggregations. However, this requires a great deal of human intervention, such as holding the uncut clay and working one clay module at a time. The clay components are also solid, which presents a number of issues when firing, such as risk of explosion in the kiln. David Celento and Del Harrow of Pennsylvania State University, have developed ceramiSkin, which explores the digital possibilities of ceramic cladding systems.[4] Like us, Celento is interested in the inherent plasticity of clay as a medium that is conducive for working with double curvature and complex geometries inspired by nature. Celento turns to nature for variegated component forms such as lily petals, which are scanned and used to generate cladding panels. However, the number and degree of variegated components is limited by the constraints of traditional multipart molds. Perhaps closest to our *PolyBrick* project, is the work and research of Ronald Rael, who started experimenting with 3D-printed dry clay recipes at the same time as our group and achieved fully fired ceramic modules and bricks for new brick and façade systems.[5] Rael is now working predominately with 3D-printed concrete.

Crafts-Based Media and Biology: Initial Prototypes

The initial impetus to work with ceramics in architectural projects was driven by an interest in hybridizing the material parameters inherent to the highly plastic nature of clay with basic part to whole relationships present in biological cellular behavior (Figure 1). Additionally, we intended to move beyond the printing of representational objects in our ZCorp 510 color printer in favor of the rapid manufacturing of parts. This effectively increases the spatial capacity of the build bed through the packing of component parts. The plasticity of clay offers up a useful material interface for projects sitting at the nexus between biology and architecture. Within the Sabin+Jones LabStudio, we started working with 3D-printed ceramics to investigate complex

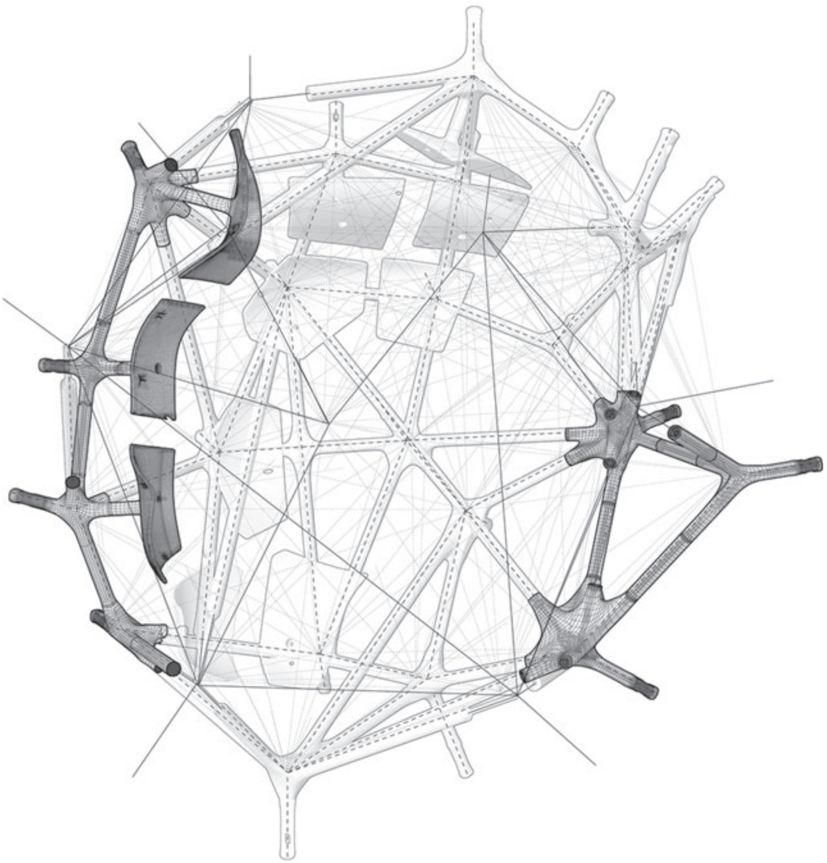

Figure 1. *Ground Substance*, the digital component model abstracted from the original biological system of study, Sabin+Jones LabStudio. Designed by Jenny E. Sabin, Andrew Lucia, and Peter Lloyd Jones. Originally exhibited at the Design and Computation Galleries, Siggraph 2009. Figure originally featured as part of ACADIA 2010: LIFE in:formation, On Responsive Information and Variations in Architecture [Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)].[6]

biological phenomena through the visualization of microscale datasets embedded in material systems. This was achieved through direct experimentation with dry clay material recipes and LabStudio's 3D printer during the summer of 2009. This was later refined in the context of three seminars on digital ceramics taught by Sabin, initially at PennDesign and now in the Department of Architecture at Cornell University (Figure 2) and later through recent spatial prototypes in the Jenny Sabin Studio (see PolyMorph for the 9th ArchiLab, Naturalizing Architecture, FRAC, Orleans, France).^{6}

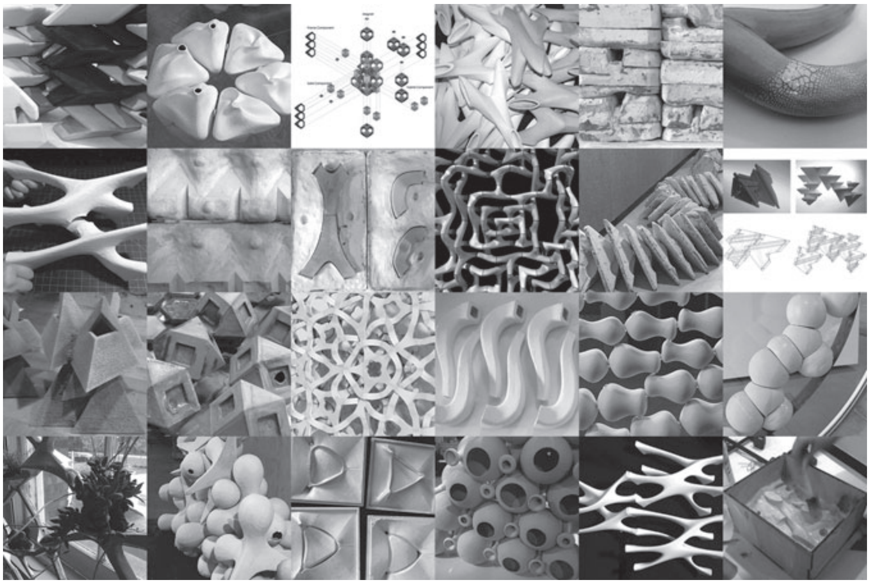

Figure 2. Digital ceramics. Selection of student work produced in Jenny E. Sabin's seminar titled *Special Topics in Construction: Digital Ceramics*. The first installment of this course was taught in the graduate architecture department at the School of Design, University of Pennsylvania. The second two installments have been taught in the Department of Architecture, Cornell University.

Figure 3. Three-dimensional (3D)-printed clay components for the project *Ground Substance* ready to be excavated from our ZCorp 510 printing bed. Figure originally featured as part of ACADIA 2010.^{6}

Ground Substance was our first project to employ 3D-printed ceramic components (Figure 3). We focused our efforts upon simulation of nonlinear behavior in cell biological systems and the translation and representation of these multicellular structures into material systems and fabrication techniques, namely through 3D printing. Additionally, we wanted to bridge behaviors abstracted from biology with material constraints, part to whole relationships in componential logics, fabrication techniques, and assembly strategies.

At the biological level, the project examines and is inspired by morphogenesis and cellular packing behavior as a response to alterations in tissue surface design. At an applied level, the project enabled advances in tectonic and material processes of nonstandard rapid manufactured component production. The final fabricated model is composed of 146 unique 3D-printed ZCorp Powder and ceramic prototype parts connected together with an internal system of aluminum rods and an external tertiary system of cable threads.

3D-Printed Ceramic Components: Adapted Recipe

The production of ceramic form includes three distinct phases: greenware, bisque firing, and glaze firing (Figure 4). Greenware is the initial state of the clay form before firing. During this phase, the clay may be manipulated through hand forming, throwing, casting, and now 3D printing. The actual clay modules in our project were directly printed using a 3D color printer. Initial recipes for the dry clay mixture were adapted and later transformed from open source recipes published by Mark Ganter who directs the Solheim Rapid Manufacturing Laboratory located in the Mechanical Engineering Building at the University of Washington in Seattle. The recipes were initially published in Ceramics Monthly

Figure 4. The greenware stage (prefiring). Excavated and cleaned 3D-printed clay parts. Figure originally featured as part of ACADIA 2010.[6]

on February 1, 2009.[7] The mixture includes 2/3 high fire (cone 10) stoneware buff dry claybody, 1/3 maltodextrin, and 1/3 extra fine sugar.

For the first set of prototypes, we chose to work with a high-fire clay body for durability and strength in parts. Each part was initially fired to cone 06 during bisque fire and then glaze fired to cone 10 or approximately 2300°F. In ceramics, kilns are not fired to temperature; they are fired to a cone level. This incorporates both temperature and overall duration of the firing process, which measures how much heat is absorbed by the clay body. During the initial firing, the clay body shrinks by approximately 15% (Figure 5). This shrinkage factor must be incorporated into design parameters when working with low tolerance models and construction techniques.

Figure 5. Initial set of prototype parts. During the initial firing, the clay body shrunk by approximately 15%. The same 3D-printed part was printed in standard starch powder (left) and in clay, then bisque fired, glazed, and glaze fired (right). Figure originally featured as part of ACADIA 2010.[6]

Materials and Methods: PolyBrick

Building upon our initial research and prototype experimentation commencing in 2009, we have developed *PolyBrick*, an assembly of nonstandard high-resolution ceramic brick components for the mortarless construction of the first fully 3D-printed and fired ceramic brick wall. Our study began with the implementation of digital algorithmic design tools, testing various methods for creating componentry within the virtual realm. Testing several means for the generation of clean mesh component models, we developed a reliable system utilizing parametric design tools within the Grasshopper plugin for the Rhinoceros 3D modeling program by McNeel and Associates.

Seeking to achieve a system that required no additional adhesives or mortar, we looked to traditional wood joinery techniques as a means of interlocking adjacent components. We developed a customized tapered dovetail in which the direction and severity of the tapering is dependent upon the local geometric orientation of each component; the tapering of the dovetail is based upon the slope of the surface being generated such that the narrow end of the tapering is always at the lower face of the generated surface. Thus, the force of gravity locks adjacent components together.

Rather than designing massive parts, we implemented a structural lattice to achieve an array of linked components, which allowed for a high degree of resolution in each part maintaining strength while saving on material usage. The lattice takes advantage of 3D printing technology and mass customization where every part is unique but coherent in its assembled whole. Direct casting of the clay bricks would be near impossible using more traditional means of multipart molds.

In order to print full-scale components, the following steps were taken. First, the larger structure was broken down into smaller components with a size and proportion that allowed them to fit in the print build and to maximize the amount of bricks per printed build. Since time becomes the largest constraint when 3D printing full scale components, it's important to design the components so that the maximum number of components may be printed in each cycle. The bricks are designed to print in a ZCorp 510 color powder-based 3D printer. This requires that the components are (1) designed to be hollow, in order to efficiently use material and time involved, and (2) designed to contain holes in order to ensure for removal of interior loose clay powder during post processing (Figure 6).

We exchanged the proprietary ZCorp powder media for our custom claybody recipe, which is drastically more cost effective. These changes in material required changes in the design to adhere to principles that govern ceramics and printing with clay, such as the rounding of edges to reduce the likelihood of chipping. The process was slow but allowed for a higher degree of accuracy and resolution. We found that printing simultaneously with multiple print heads increases the speed of the print batch and reduces wear on the printer. High accuracy and resolution allow for tolerances to be built into the digital model. Bricks are printed in a sequence that allows for rapid assembly. When one print is done, it is set aside to dry while the printer prints the next batch.

After cleaning the greenware printed bricks, they are fired to a low initial bisque fire, cone 06 (Figure 7). This initial low fire bisque decreases warping and shrinkage. However, this also increases the fragility of the part. During the first 500° of this initial firing, the

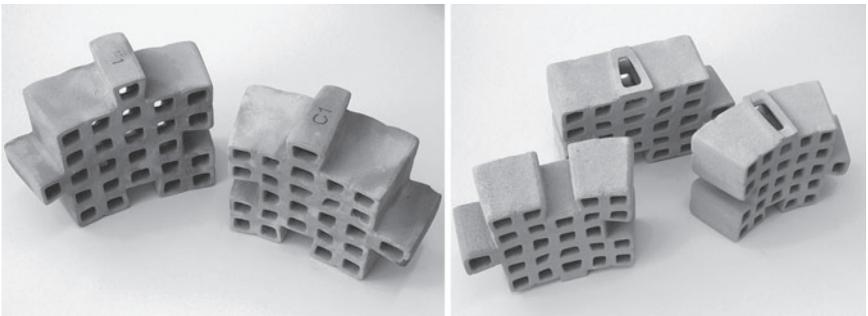

Figure 6. *PolyBrick* in greenware stage after being excavated from the 3D printer and cleaned (left) and after the first firing, the bisque fire (right).

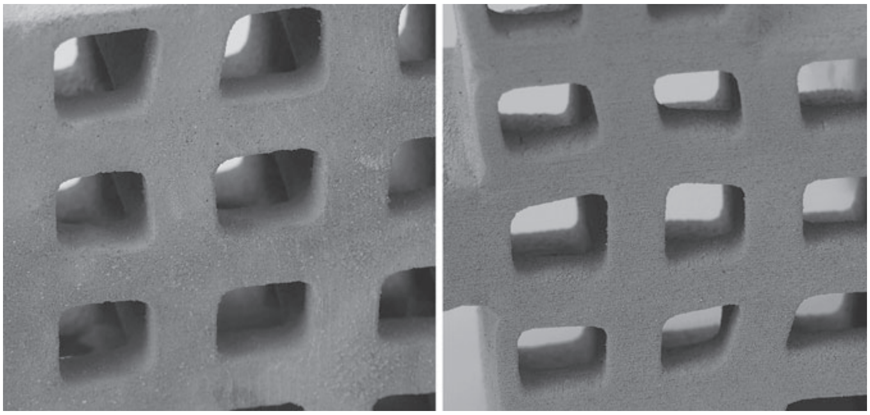

Figure 7. Detail of *PolyBrick* parts in greenware stage (left) and bisque fired stage (right). Tolerances were maintained throughout the printing and firing phases.

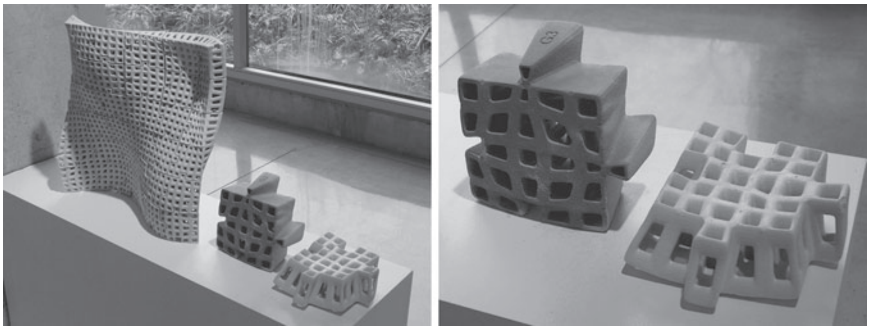

Figure 8. Final set of models and prototypes for the *PolyBrick* wall project. Scaled 3D-printed and assembled component brick model (left) and fully fired and glaze fired brick (right).

organic matter in the clay recipe, the sugar and fiber, along with the binding fluid burns out, making the part partially porous and fragile. The bricks are then subsequently dipped in a high fire satin glaze. The bricks are designed for the glaze to impregnate the tessellated interior of the brick lattice. The surface area of the brick is also maximized in order to allow for more glaze to access the brick component. Once glazed, the bricks are then fired to a higher temperature (cone 4) in order to ensure that the glaze vitrifies. Importantly, the thickness of the glaze is accounted for in the tolerances of the connection detail. Using labels that were embossed in to the digital .stl file itself, the prints are then assembled with their neighbors accordingly (Figure 8).

Results

Current 3D printing technology limits the size at which one can build. Using a component-based system, part to whole relationships and geometric specificity in terms of local orientation, we have generated a series of digital tools that allow us to create large-scale objects from a smaller print bed. Using computational design techniques, we have built a series of custom digital tools to facilitate the embedding of multiple data sets. Many wall systems require an array of materials and a significant level of human labor to construct. Our system operates using only a single material and can be put together simply and easily. The development of human large-scale 3D-printed assemblies is difficult using current 3D printing technology and those systems that can print at the human and building scales frequently exhibit very low resolution in terms of mesh fineness.

To maintain a high level of resolution at larger scales, it is necessary to develop digital parametric tools that allow for the intelligent breakdown or discretization of large-scale geometries into component-based systems. Within these component-based systems our goal is to develop a smaller scale geometry that does not simply subdivide the original geometry but rather creates a location- and orientation-based intelligence that allows the components to interlock and interface with their neighbors to create a larger variegated whole. (Figure 9)

Interlocking elements need to have awareness of their specific orientation and location within the whole system. When trying to create a system that is based on geometrical interfacing rather than adhesive or mortar, geometries can be employed to lock the pieces together. Our inspiration comes from the joinery of traditional Japanese wood construction. The dovetail in our implementation involves a spatial awareness, which alters the tapering of the interlocking pieces dependent on the slope of the surface being fabricated, such that gravity does the work, sliding and locking the dovetail into place.

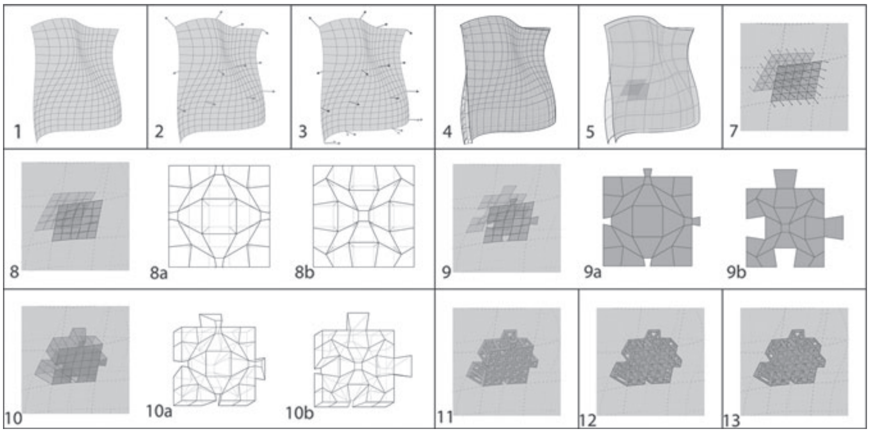

Figure 9. Customized algorithmic tooling. **(1)** Generate flat, single-curved, or double-curved digital surface within Rhino3D virtual environment. **(2)** Analyze the surface to determine normal vectors at UV grid points. **(3)** Adjust normal vectors to accommodate for the ground plane assuring that regardless of surface curvature near ground plane the base of the wall will meet the ground plane evenly. **(4)** Using adjusted normal vectors, thicken surface by offsetting respective UV grid points along respective vectors utilizing both the positive and negative magnitudes. **(5)** Subdivide new thickened surfaces according to parameters specified by the bed size of the 3D printer such that all bricks take optimal size for most rapid production and highest efficiency per print. This will determine the number of rows and columns of bricks. **(6)** Further subdivide corresponding front and back faces of each individual brick using a 5×5 grid for subdivision. **(7)** Determine local vector directions at grid points. **(8)** Deform initial 5×5 grid based on verticality of local normal vectors generating a grid that will later determine the proper tapering of interlocking dovetails for mortar-less aggregation. **(8a)** Grid transformation for faces exhibiting negative Z value normal. **(8b)** Grid transformation for faces exhibiting positive Z value normal. **(9)** Examine the local conditions of neighboring bricks; exchange single grid cells with neighboring bricks, where one naked edge will accept a neighboring bricks central adjacent cell, giving up the corresponding cell on the opposite edge. Bricks, which lie on the naked edge of initial input surface, do not exchange cells because there is no adjacent neighbor. **(9a)** Neighboring face exchange pattern for faces exhibiting negative Z value normal. **(9b)** Neighboring face exchange pattern for faces exhibiting positive Z value normal. **(10)** Generate a massive form creating solids between corresponding faces of thickened surface. **(10a)** Massing form of dovetail tapering upwards. **(10b)** Massing form of dovetail tapering downwards. **(11)** Transform massive brick into structural lattice determined by the edge conditions of determined solids. **(12)** Smooth structural lattice into curvilinear form for cleaner 3D printing. **(13)** Offset mesh surface distance determined by application of glaze to ensure proper interlocking of neighboring bricks. **(14)** Label bricks along interior faces hidden within final aggregation using orientation and embossing algorithms. **(15)** Through use of evolutionary algorithm, reorient all bricks such that each bounding box within Euclidian space achieves the lowest possible volume with the goal of fitting the most bricks into a single print bed. **(16)** Using a 3D packing algorithm, determine arrangement of respective bricks to be produced per 3D print. This part of algorithm can be adjusted to consider orders of assembly versus maximum efficiency for all print jobs.

Standard brick walls exist as a repetition of a single unit, our system exists entirely as an aggregation of unique elements. Because our bricks are generated through the mass customization of 3D printing, the repetition of form becomes redundant and detrimental to the process. The geometries of every brick can be customized to respond to numerous conditions simultaneously. For instance, a dome or wall could be constructed in which the precise thickness and hence weight and strength of the brick is dependent upon its local position within the overall aggregation, thus, generating the customized brick based on its geometric specificity and orientation in space.

The results of these methods have shown that the 3D printing of full-scale clay component systems are well within reach. The printing of the bricks is relatively cost effective with minimal labor and efficient use of low cost materials. The process is replicable for more complex geometries and is scalable. We found that increasing the number of print heads in use during the print build equates to faster build time. Although we experimented with several binder solutions with various alcohol bases, we found that using the ZCorp binder and allowing it to burn out during the first bisque fire resulted in more durable greenware printed parts. Additional printers running simultaneously would increase the number and degree of parts produced. The assembly logic is embedded in each part through embossing.

Some improvements that may be made in the foreseeable future, and some issues that may arise:

1. The components could contain more specific assemblage information for matching sides.
2. The components may be designed to use the entirety of the print volume.
3. The design of the components may shift and change during the time of production.
4. A larger array of print heads could be used to reduce wear on the mechanical parts of the printer.
5. Prints could be scanned before and after stages of firing in order to most accurately account for shrinkage and warping.
6. Our printer was not initially made for large production runs, a printer made specifically for production would be built to be more robust.
7. Inkjet technology might not be the best option for depositing large quantities of binder.

Conclusion

Leveraging the complex geometries inherently available in 3D printing, we are able to embed and respond to multiple layers of data simultaneously, creating form that can respond locally to global conditions such as structural loading, spatial context, and geometric orientation. Our process for fabrication also achieves a very high level of material efficiency creating a minimal amount of waste and requiring no additional materials for the aggregation of parts. While large-scale 3D printing technology is becoming more accessible, the drastic loss of resolution was an unacceptable compromise for our team. Thus, powder-base 3D printers do not necessarily need to be larger to start printing full-scale systems. In fact, many of the features already present in older ZCorp models allow for the full-scale production of component systems. The ingrained resolution and accuracy can provide enough information to make components that attach to each other with high levels of accuracy and extremely low tolerances. The ability to print any design allows for the embossing of assemblage requirements in to the parts themselves.

The possibility of incorporating differentiated ceramic bricks and modules in architecture through a controlled and mass-customized process that integrates design to production in one linked loop, is readily at hand through these initial prototype studies. It is now possible to embed complex phenomena in ceramic building blocks—from design to final production—through the integration of 3D-printed component design through the direct printing of clay bodies in a typical 3D printer. The plastic nature of clay offers up a material terrain for a careful and highly controlled deployment of complex and organic form. In this sense, ornament takes on a deeply structural and material realm, where code/pattern, geometry, material, fabrication, and assembly are interconnected. Operating within size limitations of our current ZCorp 510 3D printer, we developed and tested a set of mass customized components with embedded local and global awareness. We have effectively designed a system for 3D printing mortarless ceramic brick assemblies at scales and in materials well beyond existing constraints of additive manufacturing technology.

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Author Disclosure Statement

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