Design research for digital ceramics commenced with the project, “Ground Substance” an experimental form produced in the Sabin+Jones LabStudio. The design team was led by Jenny E. Sabin and Andrew Lucia. Dr. Peter Lloyd Jones and Agne Taraseviciute led the scientific team. Our design critic was Annette Fierro. The project was inspired by original biological research conducted at the Jones Laboratory, supervised by Dr. Peter Lloyd Jones and led by MD-PhD student Agne Taraseviciute at the Institute for Medicine and Engineering, UPenn. This research was supported generously by the CMREF. Design and production of “Ground Substance” was supported generously by a UPenn Research and Development Grant awarded to the Sabin+Jones LabStudio.

1 Introduction

This paper showcases revolutionary steps that we have made in the integration of complex phenomenon towards the design, production, and digital fabrication of ceramic form in the design arts and architecture. This work includes advances in digital technology, digital fabrication, advanced geometry, and material practices in arts, crafts, and design disciplines. Digital Ceramics documents the use of algorithmic design techniques for the digital fabrication and production of ceramic components at a range of scales and applications. Case studies explore the role of the ceramic component in design and architecture and its reciprocal relationship in alternate fields and industries. Techniques in parametric and associative environments are incorporated with feedback derived from material constraints as well as performance assessments. Projects interrogate the physical interface between complex datasets and fabricated material assemblies in order to address novel applications of non-standard ceramic components towards the production of 3D textured prototypes and systems. Project work follows two tracks including mold production and slip-cast ceramic component design and direct 3D printed ceramic component design.

2 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. Reinforced concrete was the building material of choice during the Modernist era, thereby
historicizing the brick and thus rendering it a building material of the past. Contemporary nostalgia for the ceramic module and technical advancements in pre-fabrication, has offered up pre-fabricated non-load baring brick façades (Keuning, 2007). Ceramic bricks and tiles, so ubiquitous in their application in the built environment, have surprisingly 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 form 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 up a potent material solution to contemporary generative design processes in architecture, which frequently feature organic and natural forms of increasingly complex expression and ornamentation. (Figure 1.)

3 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 design for quite some time. 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 on in the form-finding process. Once 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 on to engineers for component design and panel production (Clay Modeling, 2010). This process presents a very interesting transfer of information and data through the hybridization of craft-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 maximize high strength-to-weight ratio and material effect. 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 non-standard ceramic building blocks in architecture. Given its structural and material capabilities alongside contemporary advancements in fabrication, digital ceramics presents a series of intricate tectonic methodologies with scalable applications in architecture.

4 Visualizing dynamic datasets for novel material expression

In addition to forging new design strategies in the production of ceramic component systems for architectural application, digital ceramics probes material systems that express the spatial substance and personalized architectures of diverse datasets. The process gives rise to questions about
the visualization of data, technology and how we as people interface and interact with information at an architectural scale. By investigating loops that filter datasets through material organizations, several of the described projects seek to unfold and reveal matters of information and knowledge through alternative modes of access. The increased stores of information available within design technology are insisting on new models for information mediation, collaboration and “seeing” amidst an ever-increasingly complicated information context. Here, data is no longer represented as a static image, but rather in a dynamic process model, where code, geometry, material, fabrication and production are inextricably linked.

With increasing amounts of data now being generated, there is a growing demand for more sophisticated computational tools and fabrication methods that are capable of extracting and analyzing specific temporal and spatial relationships in both the sciences and the design arts. To address this problem, researchers in the Sabin+Jones LabStudio, co-founded and co-directed by Jenny E. Sabin and Dr. Peter Lloyd Jones, a cell and molecular biologist based at UPenn, are developing new approaches for the analysis, visualization and fabrication of large biological and architectural datasets. Much of the work presented in this paper calls for an intervention in this technological context through the visualization and materialization of intangible information through the use of crafts-based media, namely clay.

5 Crafts-based media and Biology

Biology provides useful systems-based models for architects to study and understand how context specifies form, function, and structure. While the first phase of our design work resides within the spirit of research and discovery, our current phase engages design-oriented applications in experimental material systems ranging from new concepts of materiality to adaptive structures and complex geometries. Key to this design research is the exploration of new tectonic organizations for application at the architectural scale. Here, material technology and design ecology are informed by the visualization of complex biological systems through the generation of new design tools and experiments in fabrication and material construction. Thus far, essential part-to-whole relationships abstracted from cell biological systems have been explored through the design and 3D printing of non-standard components on our LabStudio 3D printer.

The initial impetus to work with ceramics in architectural and design projects was driven by an interest in material relationships with woven patterns and the highly plastic nature of clay. Similar to weaving, the plasticity of clay offers up a useful material interface for projects sitting at the nexus between the biology of the body and architecture. Within the Sabin+Jones LabStudio, we started working with 3D printed ceramics to investigate complex biological phenomenon through the visualization of micro-scale datasets embedded in material systems. This was achieved through direct experimentation with dry clay material recipes and LabStudio’s 3D printer. This was later refined in the context of a new spring 2010 seminar on digital ceramics taught by Sabin.
Ground Substance, designed by Jenny E. Sabin, Andrew Lucia, and Peter Lloyd Jones with Annette Fierro, was our first project to employ 3D printed ceramic components. The project bridges art, architecture, and science through a formal and material model that is at once natural and artificial. We focused our efforts upon simulation of nonlinear behavior in cell biological systems and the translation of this behavior into material systems and fabrication techniques, namely through 3D printing. We are interested in abstracting behaviors as opposed to form and cellular shapes, which sits in contrast to popular biomimetic approaches. Additionally, we wanted to bridge behaviors abstracted from biology with material constraints, force transmission and actual fabrication and assembly as a continuous and unfolding loop. In the context of the project, there was a constant reengagement of feedback, where material and fabrication constraints informed our virtual computational models. The final suite of components engaged a process of nonlinear fabrication informed by biological behavior and novel fabrication techniques. (Figure 2).

At the biological level, Ground Substance spatializes cellular and tissue contour information based upon an abstraction of human mammary epithelial cells cultivated within a 3-D normal or tumor-like microenvironment. 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 non-standard 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 rod and an external tertiary system of cable thread. (Figure 3).

6 Cast & 3D Printed Ceramic Components

The production of ceramic form includes three distinct phases: greenware, bisque firing, and glaze firing. Greenware is the initial state of the clay form before firing. It is during this phase, that 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 mechanical engineer, Mark Ganter, in Ceramics Monthly. The mixture includes dry clay and organic materials.

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 fired to cone 10 or approximately 2300 degrees Fahrenheit. 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 25%. This shrinkage factor must be incorporated into design parameters when working with low tolerance models and construction techniques. (Figure 6)
Later studies include 3D printing of 2-part molds and components for slip casting of individual parts in multiples. Slip casting requires liquid clay or what is commonly called ‘slip.’ Initial studies incorporate high-fire porcelain for its translucency and for ease in casting. Slip casting affords rapid production of multiple parts, but with limited variation. Complexity and variation of each part is governed by the mold. By 3D printing the mold, the complexity of each cast part was significantly controlled through the initial digital model. (Figure 7.)

7 Material Behavior: Variegated Ceramic Components

Discoveries made in the context of design research carried forward in the production of Ground Substance alongside a professional knowledge of ceramics, formed the conceptual and technical scope for the graduate seminar titled Digital Ceramics: Experiments in Design Techniques. This course was taught during the spring semester 2010 in the Graduate Department of Architecture at the School of Design, UPenn. With a solid understanding of the material and fabrication constraints at hand, experimentations that commenced with the embedment of biological information for the production of non-standard components could now be exhausted in the context of additional datasets and computational sources. Students enrolled in the seminar were required to interrogate the interface between digital information and fabricated material assemblies in order to address novel applications of non-standard ceramic components and tiles towards the production of a 3D textured wall or screen prototype system. Algorithmic modeling techniques that featured iterative behavior based on nesting, tiling, and stacking were given preference. The students worked in groups and followed two integrated paths: 1) Mold Production and Slip-Cast Ceramic Component Design. 2) 3D Printed Ceramic Component Design

The course was largely composed of a sequence of workshops and lectures addressing conceptual, formal, and fabrication issues related to intersections between ceramic modules and architecture. Weekly lectures included detailed instruction on modeling, scripting, mold production, 3D printing, and RP technology and slip-casting and printing of ceramic media. Most of the architecture students enrolled did not have a background in ceramics, so significant introduction to the media and field was necessary.

The following project makes use of links found between textiles and ceramics to investigate the tectonic and component potential of knitted and woven structures in ceramics at an architectural scale.

8 Knitting and Weaving Ceramic Form

A clear translation and integration of ceramics and textiles is exemplified in the following project by recent graduate, Jennifer Trumble. The project integrates procedures native to weaving and knitting with a system of interlinked ceramic ‘stitches’ or components. The final screen system features a family of knitted and woven components produced by casting of
3D printed parts and direct 3D printed clay parts. The basic form of weaving operates on a principle of opposites. As a material, the weave is composed of many interlaced threads that together form a submissive and responsive whole. This binary system is made up of warp strands held in tension and weft strands interlaced perpendicular to the warp. Given its structural and material capabilities, the weave is able to transcend metaphor and exist as an intricate tectonic methodology with scalable applications in architecture. In Trumble’s project, the over and under procedures native to weaving are hybridized with a knit stitch. Differing from the weave, a system of discrete strings or members, the knit is a continuous system. One single member navigates the system, and in each instance looping its current self through its former self. Given these links between material, structure, and construction, the knit is rich in architectural potential. The complexity of the curvature of each stitch became a fruitful area to mine as the constraints governed by mold production and casting demanded a limited number of undercuts for the sake of extracting each cast part. The process required a constant refinement of the initial digital knit and weave simulations against constraints brought forward in 3D printing, mold production, and firing. Direct printing of the clay allowed for a greater degree of variation in each part. (Figure 8).

9 Platonic Solids and Crystalline Structures

This project by Carrie Chan, David Chen, and So Sugita began with research on crystalline structures. They settled on the simplicity of a series of platonic solids, ranging from hexagons to octagons, constructed from a set of planar parts featuring frames, surfaces, and solids. While the geometry of each individual component was quite regular, the final system features change across the whole through the simple manipulation of glaze color, placement of surface or frame, and packing strategies. To cast each part, sophisticated 2- and 6-part molds were produced with accompanying jigs to limit the degree of change in each part. 3D printing the clay frame components significantly increased the speed of execution and decreased the risk of imperfections in each part. Given that this packing system exhibits low tolerances, precise casting measures had to be taken into account. Of significant note is the degree of novelty in the ‘mortar’ used to connect each final glazed and fired ceramic part. Connections between components were made with high strength magnets embedded in the tops, sides, and bottoms of each part. (Figure 9, 10 & 11).

10 Adjusting Component Geometry and Assembly

Ghost diagrams serve as the starting point for this project by Emaan Farhoud, Gera Feigon, and Andrew Swarztell. A ghost diagram is a particularly useful algorithmic tool for ceramic component production as it takes specific sets of tiles as input and attempts to find patterns into which they may assemble and connect as a whole. Ghost diagrams come to us from mathematics and have connections to calculus and cellular automata simulations. Of interest to
us was how the ghost diagram may be used to design a family of components that could be assembled in multiple ways through simple connections. After studying the properties of ghost diagrams available on the web, the students designed and wrote their own ghost diagram simulation to customize their component design and production. (Figure 12, 13).

11 Reinventing the Ceramic Tile: Locating Surface and Frame in Penrose Geometry

The Penrose tile is a well-known aperiodic tiling system that exhibits reflection symmetry and five-fold rotational symmetry. More specifically, because the system does not exhibit translational symmetry, a shifted copy of a tile will never match its original state. These concepts have been well researched and have been discovered in ancient and medieval Islamic Architecture. However, there has been little done in the architectural application of the three-dimensional qualities of the Penrose tile, which may be found in nature in quasicrystals. In this project by Christopher Allen and Tang Han, the three-dimensional qualities of the Penrose are investigated in line and surface, as a series of overlapping and undulating figures in space. The final suite of tiles is the result of a series of productive failures whereby the nonperiodic quality of the Penrose is joined with the constraints found in clay and tile production. (Figure 14, 15 & 16).

12 Altering Growth Patterns through ‘Mortarless’ connections

The pyramid is a difficult geometric primitive to transgress. Students Matt Choot, Rebecca Fuchs, and Alexander Lee chose to work with the simplicity of a pyramid-shaped component in combination with a generative growth system that at moments allowed the omnipresent qualities of the pyramidal component to fall away in favor of global behavioral effects exhibited by the system. This was given emphasis by their unique glazing technique, which incorporated air-brush glaze gradients across the component bisque ware. Early on in the project, the subject of mortar was broached in the pursuit of designing efficient and aesthetically pleasing joints between components. 3D printed studies afforded some beautiful discoveries in slide-and-lock surface connections, but given that the connections required very low tolerances, it was not possible to transfer this initial design to ceramic media. In combination with a spiraling growth system, connections were designed that also factored in as a variable to control the spiraling behavior in both digital and final analog assemblies. Of significance is that the actual pour spout where the clay slip is initially poured in the mold, was later used as the connection point between components.

Sophisticated molds are designed and produced to generate multiple castings in one pour and to promote efficient extraction from the mold. The spiraling action of the designed growth pattern (upper left) is figured in at the connection detail as an analog variable for controlling spiraling.
13 28 Different Connections: 1 Component, Same Topology

There were six group projects completed during the first installment of Digital Ceramics: Experiments in Design Techniques 2010. The last featured project by Jingyi Zhao, Liwen Mao, and Yiqin Wang was extremely challenged by the constraints put forward by the production of plaster mold-making, as their component designs were highly complex in their surface topology. However, this complexity was tamed in the fact that the entire project was generated by one component that featured 28 different connection types. The complex curvature of the component inspired additional design mechanisms in the production of molds, including a jig that would keep the cast clay arms straight as they air-dried. The final set of direct 3D printed clay prototypes, worked very well for their particular project, but suffered from inconsistencies in the thickness of the actual clay part and firing rates. (Figure 18, 19).

14 Conclusion

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 phenomenon in ceramic building blocks—from design to final production—through the integration of 3D printed component design and mold production for the casting of unique and varied parts, alongside 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. This is much more than a physical product, but is an architectural concept where geometric figures, matter, and form reside. This work embraces established disciplines in a collaborative environment devoid of boundaries, sifted through, compiled, and applied by architects, artists, and scientists alike. Here, the architect is a conceptual weaver working backwards, forwards, and across linked datasets to visualize micro-scale data for novel material expression and communication at the architectural scale. Loose loop and tight loop configurations give rise to new rhythms, new effects, and technological leaps situated at the nexus of art, architecture, and science. Digital Ceramics presents a body of work situated at this pliable and calcified interface.

References