ceramiSKIN
Digital Possibilities for Ceramic Cladding Systems

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CERAMISKIN IS AN INTER-DISCIPLINARY INVESTIGATION BY AN ARCHITECT AND A CERAMICS ARTIST EXAMINING NEW POSSIBILITIES FOR CERAMIC CLADDING USING DIGITAL DESIGN AND DIGITAL FABRICATION TECHNIQUES. Research shown is part of an ongoing collaborative residency at The European Ceramics Work Centre.

Ceramics are durable, sustainable, and capable of easily assuming detailed shapes with double curvature making ceramics seemingly ideal for digitally inspired “plastic” architecture. The primary reason for the decline in complex ceramic cladding is that manual mold-making is time-consuming—which is at odds with today’s high labor costs and compressed construction timeframes. We assert that digital advances in the area of mold-making will assist in removing some of the barriers for the use of complex ceramic cladding in architecture.

The primary goals of ceramiSKIN as they relate to digitally assisted production are: greater variety and complexity, reduced cost and time, a higher degree of accuracy, and an attempt to facilitate a wider range of digital design possibilities through the use of a ceramics in architectural cladding systems.

The following paper begins with an overview discussing double curvature and biophilia in architecture and their relationship to ceramics. This is followed by detailed commentary on three different experiments prior to a concluding summary.
1 Introduction: Plastic Architecture and the Quest for Double Curvature

Current architectural investigations are exploring complex curvilinear forms in ways that go well beyond the predictions in Theo van Doesburg's 1924 manifesto, Towards a Plastic Architecture. The irony is that rather than using a truly plastic material capable of double curvature, the majority of these creations are fabricated by aggregating planar or single curvature materials, thus, approximating double-curvature, such as Gehry's notable Guggenheim Museum in Bilbao, comprised of myriad titanium panels.

While concrete and composite constructions are capable of double-curvature, form-making from other (predominantly planar) materials is required in their fabrication. A notable deviation from standard concrete forming is the work of Mark West, Director of the Center for Architectural Structures and Technology at the University of Manitoba. West is exploring the use of fabric forms for reinforced concrete creating unusually complex, lightweight, high-efficiency structural shapes. (See http://www.umanitoba.ca/faculties/architecture/cast/)

Nearly a decade ago, Bernard Franken attempted an ambitious project in glass that features double-curvature with his 1999 BMW pavilion based upon intersecting soap bubbles. The design was envisioned to be fabricated solely out of monolithic double-curved glass panels. The glass readily assumed these shapes with good precision, but ultimately the loads exceeded the sealant’s structural capabilities, requiring additional structural framing for support.

2 Why Ceramics?:

Ceramics were once the material of choice for neoclassical architectural terra cotta facade systems for reasons which remain applicable today. Not only are ceramics capable of plastic effects with double-curvature, but they perform well under compression, aggregate easily with grout, resist corrosive forces, and may be glazed in durable colors. Today, rather than witnessing greater complexity in ceramic cladding, the reverse is generally true, with solutions predominantly using repetitive flat tiles. This trend may be changing with the recent introduction of uniform terra cotta extrusions. These units were used at the Harvard Center for Government and International Studies by Pei Cobb Freed (2005), as well as the Ross School of Business by Kohn Pederson Fox—which is currently under construction and will be LEED certified.

Considering the increasing importance of sustainability in architecture, ceramics offer several useful properties. Ceramics may be produced locally and contain lower embodied energy than many alternative sheathing materials (measured in megajoules per kilogram, ceramics is less than 1% of titanium and 3.5% of copper) thus, satisfying several LEED criteria. (See http://www.canadianarchitect.com/asf/perspectives_sustainability/measures_of_sustainability/measures_of_sustainability_embodied.htm/). Glazes, which formerly contained heavy metals, are now produced which are more environmentally friendly and equally durable.

While historically, ceramics were often used in lieu of stone due to the reduced cost to obtain and shape, the ability for ceramic glazes to retain vibrant color was (and largely still is) without equal. Ornamentation is also an area in which ceramics excel, permitting easy casting and carving, enabling such works as Louis Sullivan’s Guaranty Building of 1896.

While the popularity of ornamentation has gradually declined in architectural spheres since the publication of Ornament and Crime (Loos, 1908) and the advent of Modernism, there is renewed interest in the topic as evidenced by The Function of Ornament (Mous-savi, Kubo 2006), and the new exhibition Re-Sampling Ornament at the Swiss Architectural Museum in Basel. With digital fabrication techniques gaining popularity due to reduced labor costs and increased potential to realize complex forms, ornamental inquiry is poised to expand—embracing both traditional ornament, as well as complex parametric explorations. One such example of the latter is the Wall of the Future by Contemporary Architectural Practice seen in the recently opened exhibition at the MoMA Home Delivery: Fabricating the Modern Dwelling.

The drawbacks to ceramics include relatively low tensile strength, weight, slight shrink-
Due to mutual interests in natural forms, as well as the challenges inherent in accurate data capture and production of these shapes, we chose to begin our investigation with biophilic inquiry. It is important to note that our work at this stage is more focused upon formal consequences of natural form and their production techniques. While this suggests some structural implications, the primary focus of our work is formal, not biomimetic,—meaning that we are not seeking to imitate natural systems in order to create novel solutions, but rather we are attempting to capture, emulate, abstract, and translate them.

Edward O. Wilson, the renowned Harvard biologist, commenting on the natural world uses the term biophilia to describe “the connections that human beings subconsciously seek with the rest of life.” (1984, 1993). Continued inquiry in this area by Stephen Kellert, Judith Heerwagen, and Martin Mador (2008) identifies early research supporting health benefits resulting from biophilic environments. Going beyond this observation is James Wise, an environmental psychologist from Washington State University, who (controversially) suggests that it is the fractal patterns in nature that are primarily responsible for beneficial human responses. Further, Wise believes that these natural patterns can be mathematically reproduced with the same beneficial affects as those in nature. (2006).

Natural structures received much attention in architectural and engineering circles during the past century following publication of On Growth and Form, by D’Arcy Wentworth Thompson in 1917. Numerous experiments and structures related to natural forms were explored involving such things as soap bubbles (Matzke, 1945; Lewis, 1949), thin shell structures (Pier Luigi Nervi, 1891-1979), and polyhedrons (Buckminster Fuller, 1895-1983); however the tools for analysis then, as compared to today, were somewhat crude and speculative. More recent works on the topic are found by Peter Pearce (1980) who published Structure in Nature is a Strategy for Design and Frei Otto (1995) who wrote Finding Form: Towards an Architecture of the Minimal, suggesting continued relevance of organic matter to designers.

The natural sciences have utilized digital techniques less for purposes of novelty, but rather with a teleological emphasis on analysis and comprehension. Recent discoveries in the sciences, along with software that accurately models the behavior of matter, offer potential to further extend at least a century of architectural and engineering investigations in the area of natural forms, with far greater specificity. Due to the increased clarity of recent scientific analyses—and the resulting data which is often usable in design software environments—natural investigations seem worthy of more attention in design spheres than they are currently receiving, and ceramics appear well-suited for such pursuits.

These observations provoked the following question as a starting point in our inquiry. Since natural orders eschew rigid manifold geometries in favor of plastic shapes with compound curvature, is it possible to combine analytical data with digital fabrication techniques to produce easily mass-customizable ceramics?

4 ceramiSKIN Initiative:

Focusing on the digital milieu for both design and fabrication, we chose to address a wide range of data types and formats culled from atypical sources for design to confirm that our workflow would yield usable results from a variety of data. While these efforts are still incomplete, the results have been encouraging, with each experiment discussed briefly in the following sections.

Biophilic matter in architectural ceramic cladding suggests large numbers of similar, but not entirely identical pieces. This presents a challenge to traditional methods for mak-
due to the unique geometry of each of our pieces, it is important for us to be able to produce complex multi-part molds quickly and inexpensively that are capable of providing detail and relief, as well as permitting precision fitting of tiles. Point cloud data from laser scanning or particle physics generation is well-suited to this due to the creation of precise interlocking tile systems for two-dimensional polygons and three-dimensional polyhedrons.

Regarding form generation we have explored three different design methodologies. At this stage the work is intentionally wide-ranging and of various scales, favoring breadth to better inform future efforts regarding depth:

- Experiment #1 utilizes laser scanning of existing natural matter in conjunction with slip-casting.
- Experiment #2 relies upon unfolding of computationally generated fluids modeling, realized through hand-molding processes.
- Experiment #3 explores extrusions based upon historical Girih tiling in Islamic architecture.

5 Experiment #1: Laserscanning of Lily Petal and Slip Casting

For our first experiment we chose to accurately reproduce a complex natural form in porcelain. A flower petal was chosen because its formal properties are plausible as a complex building skin. With the hope that we might also use microscopic data in this endeavor, we approached Penn State’s Cytometry Facility and reviewed floral data in their confocal microscope archives. After evaluating these files (which are fascinating color raster image slices), we decided to consider both tulip and lily petals due to the complexities of their shape and the high quality of microscopic data available. Based upon experience gained
from a previous research project done while at Harvard GSD using laser scanning entitled “SPLAST” (Celento, 2007), we decided that this technique was the most suitable one to capture the delicate subject matter.

After evaluating results from laser scanning, the lily petal was selected due to its highly complex shape. Point cloud data was then manipulated in Geomagic (a surface analysis tool used in the aerospace industry) to both patch holes and reduce the surface curvature to two percent of the original. This was done to create a surface description comprised of faceted shapes. (It is worth noting that this faceting process was done solely for formal intent and was not necessary to the process.) The digital model was then sliced into sections in Maya, tooling paths were generated in VisualMill, with positive foam molds milled by a three-axis CNC. These foam pieces were then cast in plaster to permit slip-casting of smaller elements in porcelain. The slip-cast pieces were dried, then bisque fired at approximately 1,100°C to strengthen the pieces. Glazing experiments followed. The entire assembly is approximately three feet long, with each slip cast unit about one foot in length. The dimensional choice and the parting lines could have been to any scale desired, but were dictated in our situation primarily by the CNC gantry height and the size of the kilns available.

Benefits: A high degree of surface relief due to the homogeneity of the mixture, smooth glazing effects, and fairly precise fit between units. The tooling marks from milling were initially considered undesirable at the time of milling, but were felt to add to the visceral quality of the finished piece, once glazed.

Challenges: A large amount of time was spent creating plaster casts for molds, which seems wasteful if they are to be used only once during production.

Future Inquiry: Instead of creating plaster molds from CNC parts, we wondered if it might be possible to directly mill plaster molds and eliminate this time-consuming step? As yet, this is untested, but planned. Additionally, microscopic data is to be investigated for both topological surface effects and digitally printed glazes.

6 Experiment #2: Digital Fluid Simulation and Hand Molding

Our second experiment (initiated at EKWC and still in progress) was primarily focused upon expedient mold production, using hand-molding instead of slip-casting. The formal matter was based upon the particle physics engine RealFlow used to create fluid effects in the film industry, which we experienced success in rapid prototyping with a ZCorp printer. First we created a shape by defining fluid properties, then converted the point cloud data into flat triangular planes in Rhinoceros, offsetting side-walls to create hexagonal units. The data was digitally unfolded in Rhinoceros, plotted on paper, then used as templates to build plywood molds with each cell measuring almost three feet across. A very stiff mixture of reinforced clay was rolled into flat sheets one and a half centimeters thick, then hand pressed into the molds. The resultant fifteen units may be bolted together to serve as a free-standing structure, or fastened to a wall to create a waterproof membrane with grout installed between the units. We created both solid units and a few units with voids carved into them, and performed preliminary glazing experiments. Fifteen pieces were bisque fired and await glazing and assembly.

Benefits: Strength of assembly, ability to serve as cladding as well as a freestanding sculptural object, ability to fasten units together as well as fastening to sub-assemblies.

Challenges: Shrinkage of units and deformation of side-walls occurred over large spans. The primary challenge was an unexpected consequence of the offsetting process in Rhino which created twisted planes in the side-walls which prohibited plywood construction of the sides. Triangulating these side-walls will correct this, but doubles the effort to construct them. Other consequences include: residual seaming between clay sheets and a somewhat rough texture. (These attributes we found desirable, but others may not share this preference.)

Future Directions: Resolve side-wall twisting. Finite element analysis would improve fastening methods. Smaller side-walls, might diminish weight and reduce deformations, as well as enhance capabilities as a surface cladding material.
7 Experiment #3: Penrose Patterning and Extrusion Process

Our third experiment (initiated at EKWC and still in progress) evolved from a desire to explore the extrusion process, as well as an interest in historical precedent for laying out complex, non-repeating tile patterns. Thus, it is based upon the use of Penrose geometries inspired by the research of physicist and Harvard doctoral student Peter Lu into Girih tiles. He has described a conceptual breakthrough that occurred around 1200CE when tile patterns were “re-conceived as tessellations of a special set of equilateral polygons” in Islamic architecture. This allowed for precise patterns to be developed over large surfaces using aperiodic Penrose patterning. (Lu 2007)

Using the five Penrose patterning geometries, we attempted to make extruded clay forms which could be stacked to construct screen walls for arid climates. Similar to traditional techniques, these walls would permit shading and light filtration; however, because the units feature an interstitial space, water could be introduced between the units to enhance passive cooling effects. After establishing a pattern in PowerCADD, steel dies for the extrusion machine (“pug mill”) were lasercut, then clay was extruded through them to form the desired shapes. The Penrose geometries were intersected with the lily petal scan, then using an unfolding process in Rhinoceros, the results were printed to paper. The intention was for the open ends to be trimmed to replicate the curvature of the lily petal scan. As such, when the units are aggregated, the surface of the lily petal will be evident at the open ends of the extrusions.

At this point we encountered an unforeseen problem. During the unfolding process requisite triangulation of the forms obscured our original ruling lines and the templates proved impossible to match to the extrusions. Thus, the results shown involve free-form sculpting techniques in order to study the perceptibility of curvature. If this experiment is to be repeated, alternative unfolding software seems necessary. Fortunately, tests indicate better results with Pepakura—an inexpensive origami software. Due to time limitations at EKWC, the pieces were bisqued, but not glazed. Planned work involves glazing of the hollow interiors to enhance light transmission and diffusion, while the unglazed exterior will permit absorption and retention of water for cooling.

Benefits: Small units easily transported and assembled, light filtration and cooling, variety of patterns capable. Extrusion process is quite fast. Orthogonal assemblies may be addressed by trimming prior to bisque firing.

Challenges: Extrusions are sensitive to deformation through handling until dry. Patternning requires manual labor, and tracking of units to assemble desired geometry.

Future Directions: Extrusion size was limited to a 120 cm diameter sphere due to pug mill size. We speculate that if this system proved useful that a CNC wire cutter could be devised that could easily trim the edges into desired shapes, thus eliminating the time consuming conversion of forms to paper templates with requisite manual tracing.

8 Summary

Our research, while still preliminary, suggests promise for three different types of digitally
enabled fabrication techniques for ceramic cladding systems. As opposed to traditional hand techniques, digital advances for production would better enable ceramic results using a variety of data—be it analytical, mathematical, or sculptural. Digital techniques for fabrication would greatly assist in the exploration of a range of surface effects that include: biophilic results, complex ornamentation, as well as a host of other parametric possibilities.

The mediated nature of digital design has generated novel shapes that may be propagated and manipulated in almost limitless ways digitally—however, physical realization remains a challenge for many of these forms. Certainly many geometries may suitably approximate the desired shapes through planar and single curvature methods, but ceramic cladding offers the potential for double-curved surfaces, along with high levels of detail. These features, combined with other benefits from both a material and environmental standpoint suggest that digital advances in mold-making may greatly increase the use of ceramic cladding systems in architecture.

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10 References
