Prototyping Digital Ceramic Lattice Structures

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This paper will discuss the digital design and fabrication of a series of complex lattice structures and three-dimensional tiling systems as ceramic material prototypes and modular architectural assemblies. The research investigates integrating innovative digital technologies with traditional manufacturing techniques for earthenware ceramics and slip-cast plaster mold reproductions for climatically responsive building systems. As a result, a series of geometrically complex assembly designs and irregular three-dimensional tiling systems were developed and produced in a stoneware ceramic. These open geometries, based on cellular lattice structures permitting the free movement of air and light, as in screen wall architectural applications, would typically have been difficult and prohibitive to produce due to the high degree of difficulty in producing the molds and forming the necessary parts. In order to simplify the production and maintain a greater level of precision, a number of digital technologies were applied to streamline the process. By introducing various digital fabrication techniques at differing stages of the design and production process, the efficiency of traditional ceramic production is balanced against the more versatile rapid prototyping technologies. As a result, highly articulate and formally complex modular ceramic systems were realized as reproducible modular ceramic parts, which were then assembled as stable lattice structures for bioclimatic architecture in hot-humid and dry-arid climates. Various digital fabrication technologies were considered, from 3D printing models directly into a stoneware ceramic medium, as well as hybrid methodologies, such as casting reproductions of 3D printed original parts and casting production pieces from master molds milled on a computer numerically controlled (CNC) router. The digital design and manufacturing processes investigated through the production of the finished prototypes and structural lattices will be discussed.

INTRODUCTION

Perforated wall systems, trellis structures, and lattice screens are important architectural typologies that blur the transition between interior and exterior spaces, creating privacy by averting direct view lines, cooling semi-enclosed spaces by providing plentiful shading while allowing unimpeded airflow, and improving interior lighting by preventing glare and diffusing direct sunlight before it reaches building interiors. The versatile properties of these lattice structures present many useful possibilities for low-energy sustainable design through variations in pattern, porosity, and depth. By acting as porous buffers and useful architectural barriers, open lattice structures help meet the thermal comfort requirements of buildings while resolving architectural conditions with varying degrees of enclosure. Screen walls temper the climate directly at the envelope, rather than depending on thermal loads being resolved internally with energy intensive mechanical systems that are often not available in remote locations. Dating as far back as stone trellis or lattice structures used in ancient Rome and Egypt, there are many vernacular and historical examples where perforated screen walls are employed effectively to resolve difficult thermal comfort challenges in extreme dry-arid and hot-humid climates, that would otherwise be difficult to resolve without mechanical equipment. Dependence on mechanical systems unnecessarily places excess demand and energy loads on building interiors, rather than the exterior envelope, increasing the overall energy usage of modern buildings. Sealed buildings cause similar adverse effects in the microclimate around buildings. As buildings offload excess heat to their surroundings, local temperatures rise contributing to the urban heat island effect.

Traditionally, in hot-humid climates shading screens are often used instead sealed wall systems, providing for the free movement of airflow minimizing thermal mass, while still offering plenty of shading and blocking direct solar gain. In dry-arid climates where thermal mass and heavier construction are important to take advantage of

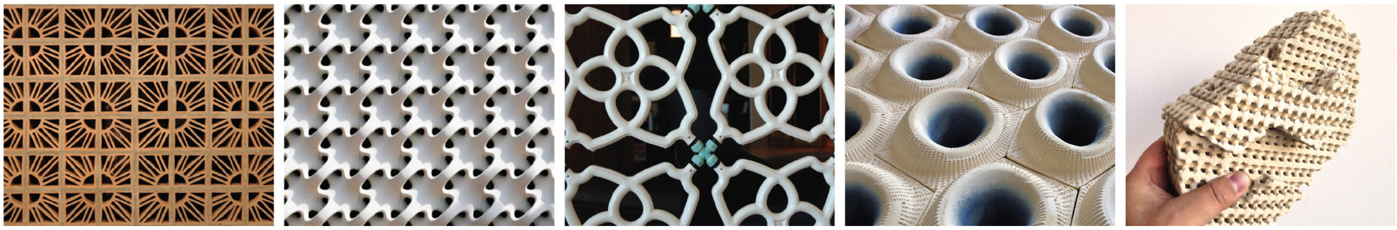

Figure 1: . Left to right: A Cobogós brick pattern, Erwin Hauer's Continua, Ecooler lattice, EcoCeramic masonry system, the 3D printed Cool Brick.

high diurnal swings and night-flush cooling, numerous small perforations through mud brick or adobe wall systems are used to provide airflow, diffuse daylight and light interior spaces, or recharge thermal mass with cool night air. Due to the low humidity in arid climates water readily evaporates removing heat from hot, dry air reducing temperatures and producing a localized evaporative cooling effect around bodies of water. Based on the water capacity of hot, dry air it is not unusual to see as much as 20-30°F cooling strictly from evaporation, provided that the relative humidity is low enough. Historically, this phenomenon has been used for localized cooling by placing water features and fountains in depressed or enclosed courtyards. This phenomenon has also been exploited for thousands of years by storing water in clay jars, a practice common in many cultures; called *zeer* in the Middle East, *botki* in Spain or *matka* in India and Pakistan. Earthenware ceramics are porous at the microscale, consequently, water will slowly weep through clay jars and forms beads on the surface. As water forms on the exterior surface of these jars, it evaporates cooling both the surface and the remaining water in the jar. In traditional Middle Eastern architecture, a *zeer* is often combined with traditional mashrabiya screens in special alcoves (called *maziara*) to cool air before entering interior living spaces, or with even larger more prominent tower features to draw in cool fresh air from wind scoops (*matkaf*) or cool towers. [1] By employing evaporative cooling strategies, porous envelopes for shading and airflow can be similarly augmented further for additional cooling potential in hot dry-arid climates.

SCREEN WALLS IN MODERNISM

In Brazil, the cobogós brick walls popularized as a more modernized example of traditional perforated screen walls and lattice systems. (Figure 1) The cobogós is essentially extruded brick turned on its side revealing the internal cavities as perforations in the wall system, resulting in a building system composed of modern structural brick or cementitious masonry units that is both structural and highly porous to allow plenty of light and air into semi-enclosed and interior spaces. The modularity of the system allows for a high degree of customization that can be adjusted for a variety of architectural applications, as well as a wide range of bioclimatic strategies for environmental controls and thermal comfort [2]. Cobogós walls were widely adopted after their invention in the 1920s, and are now an almost ubiquitous part of modernist tropical and desert architecture. These perforated walls were a significant influence and addition to the emerging modernist architecture at the time, influencing significant figures, such as Erwin Hauer, a pioneer in modular constructivist envelope and interior screen wall design, beginning in the 1950s. [3]

Erwin Hauer developed wall systems and room dividers adapting the use of screen wall systems for shading, daylighting, and interior lighting. Focusing on smooth saddle-shaped (anticlastic) geometries that could be tiled repeatedly and maintain continuity from one module to the next, Hauer developed multidimensional forms with a high degree of visual complexity that could still be efficiently assembled as modular structures. These concave-convex surfaces produce smooth transitions for diffusing daylight with subtle gradients from light to dark preventing visual discomfort from glare while producing a dynamic play of light and shadow as sunlight changes over the course of the day. These geometries proved especially useful as light diffusers even in cooler temperate climates, by integrating with more modern enclosures and glazing for sealed envelopes. [4]

BIOCLIMATIC WALL SYSTEMS

There are several contemporary examples of perforated ceramic wall systems that integrate evaporative cooling as a bioclimatic strategy for thermal comfort in dry-arid climates. The EcoCeramic cool wall takes advantage of the evaporative cooling process by promoting shading and airflow through a perforated wall system. This system relies on a ceramic face tile with a deep opening protected by a self-shading brim that directs and channels air through the wall. A drip system wets the interior of the tile, water then seeps through and weeps from the exterior surface, evaporatively cooling air as it filters through the wall. [5] The Cool Wall employs a lace-like modular ceramic screen that is fitted together using four-sided plumbing fixtures, allowing water to be piped through the modules like radiant heating or cooling systems for the evaporative cooling process, creating a localized cooling effect around the screen wall. [6] The Cool Brick presented to the Data Clay exhibition in San Francisco, like the cobogós brick, combines the principles of the *maziara* window with its *mashrabiyah* screens and *zeer* earthen jar into a single compact brick for architectural construction. The wafer like brick is produced using new fabrication techniques for 3D printing in ceramic materials, producing macro porosity that allows airflow, while dramatically increasing the surface area for evaporation. [7] With the introduction of 3D printing in ceramic materials and mass customization even more complex solutions can be easily produced. One such example, the Bloom pavilion designed by Emerging Objects, was fabricated by 3D printing individual structural blocks in a ceramic material, resulting in a wall system composed entirely of unique modular blocks

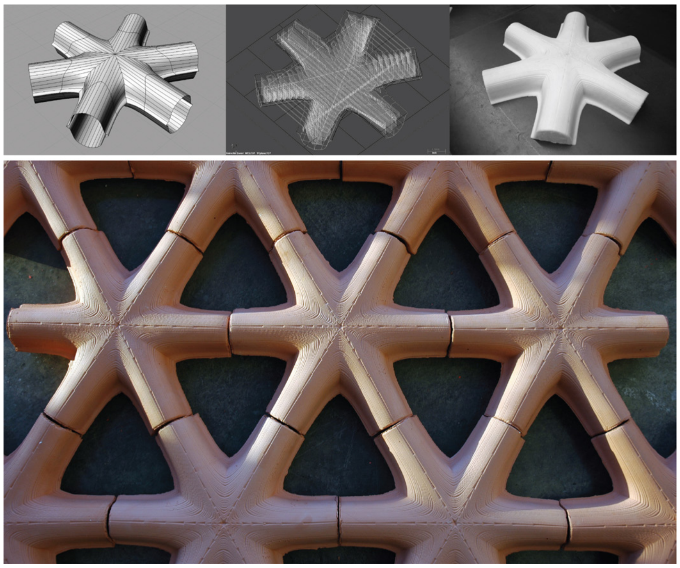

Figure 2: Original 3D geometry model, CNC router tools paths, and cast positive geometry (top). Fired and assembled terracotta modular screen wall (bottom).

digitally designed and printed, each with unique apertures controlled parametrically in the computer model. [8]

FABRICATING TERRACOTTA LATTICEWORK

A terracotta lattice system that the current work is based on, was designed as a screen wall for shading and cooling semi-enclosed spaces in a dry-arid climate. The simple lattice structure was designed and cast in a terracotta ceramic. The terracotta material offered additional structural strength over low fire ceramics, while still providing the porosity to absorb water and take advantage of the evaporative cooling process. Terracotta, like similar earthenware materials has a porous microstructure, making it an especially useful material thermodynamically for dry-arid climates. The terracotta absorbs and holds water, while air moving through the system is cooled by water evaporating off the structure creating a microclimate for courtyards or porticos. (Figure 2)

In order to form the type geometry needed at full scale, the pieces needed to be formed using a slip-casting process. Ceramic slip is a clay body produced by adding a deflocculant agent, a substance greatly reducing viscosity so that the clay behaves as a liquid and can be poured into molds without greatly increasing the water content. This produces a fluid clay body that can be used for casting complicated forms as hollow vessels. Slip is easily poured into the cavity of a plaster mold, and the dry plaster will absorb water from the slip leaving a clay shell solidified on the surface of the mold that remains as the excess slip is poured out. Due to the physics of the molding process and the shrinkage of the clay in the mold, an enclosed geometry was design as a repeating module for the terracotta screen wall. This would allow the shape to easily shrink away from the plaster towards its center of mass without tearing itself apart in the mold.

A process combining both digital fabrication and traditional ceramic forming methods was selected to translate the system from the digital model into terracotta. 3D computer aided design (CAD) modeling was used to develop the design, and the master molds for the system were cut using a CNC milling process leaving rough toolpaths. The toolpaths were left to become an artifact of the milling process revealed in the final piece in order to increase surface area and hold water for the evaporation process. Once the milling process was completed, traditional slip-casting and plaster molds were used for casting the terracotta material and forming the pieces to the desired thickness. Not unlike the digital fabrication process, slip-casting is geared towards rapid manufacturing and quickly producing multiple reproductions relatively quickly from a single mold. As the liquid slip is poured into a plaster mold, clay builds up on all of the complicated surfaces left by the milling process allowing for difficult castings to be quickly produced with a high degree of detail. The finished wall system was then tiled continuously in a repeating hexagonal pattern. The inherent strength of the terracotta material once fired, allows the lattice structure to absorb and hold significant amounts of water while maintaining its structural integrity. Similarly, due to the precision of the geometries that can be formed, the modules were assembled without the aid of mortar or adhesives by applying a simple post-tension system to lock the pieces in place using fittings and diagonal cables running through the hollow cavities of the modules. [9]

3D CERAMIC LATTICE STRUCTURES

After constructing the terracotta lattice, the structure was re-envisioned as a three-dimensional tiling system, similar to a spaceframe that could potentially be built as a self-supporting free-standing structure. Originally the design was conceived as a complicated network with a high number of irregular spans. However, it was left undeveloped beyond conceptual drawings and models, until the system was revisited with more recent explorations at the smaller more ergonomic scale of a household vessel. These studies of structural lattices focused on 3D packing geometries and open cell structures, presenting a possible solution for creating visual complexity while still simplifying the structure and drastically minimizing the number of unique elements. The 3D lattice, could then be composed of as few as only three parts tiling continuously in all directions. This system was first realized by developing designs for an ergonomic interface between a user and a hot or cold vessel. Similar to the original studies for architectural screen walls, this design was focused on the application of these structures as a thermodynamic buffer. The lattice was applied as a relief on the vessel creating additional geometry for the hand to grip, as well as providing protection when the vessel is hot or reducing heat transfer between the vessel and the hand or the table. The final piece was then translated directly into a kiln-ready stoneware ceramic material using an innovative process for 3D printing in ceramic clay bodies. (Figure 3) The final piece was then glazed using a traditional celadon glaze. Although 3D printing directly in the desired ceramic material proved to be a significant time saver, the process was not nearly as cost effective

Figure 3: Structural lattice based on 3D packing geometries (left), and the final 3D printed ceramic vessel (right).

as slip-casting. So, to begin scaling up to more typical scales for architecture, a process combining elements of digital fabrication and slip-casting was revisited for the next series of prototypes.

In order to translate the system to an architectural scale, the 3D packing geometry was first modified to meet the needs of an architectural screen wall by adjusting the thickness and porosity of the structure in order to respond to environmental loads and programmatic needs in a dry-arid climate. The overall structure was thickened to add mass to the system, while opening sizes were reduced to provide additional shading. These adjustments also help improve the efficiency of the cooling process by forcing air moving through the system to follow a circuitous path, and interact with as much surface area in the lattice as possible. The added complexity of the three-dimensional lattice promotes turbulent airflow and dynamic exchanges of air as it interacts with the system. As a result, more surface area produces more wet ceramic, which when combined with turbulent airflow, results in increased water evaporation drawing more heat out of the air. As a result, the ceramic lattice decreases thermal discomfort, provides good light diffusion and shading, as well as reducing discomfort from excessively dry air by increasing humidity levels. (Figure 4)

The final pieces were then produced by slip-casting with a stoneware clay body. By reducing the complexity of the assembly, fabrication was similarly streamlined taking advantage of the efficiency of the slip-casting process. By appropriately subdividing the geometry down to three unique pieces, all the required pieces were made using one set of plaster molds. The pieces where first bisque fired, then finished with a celadon glaze and glaze fired to a higher temperature, and then finally assembled into the final prototype. (Figure 5) Based on additional studies, it was determined that due to the porosity of these materials at the micro-scale, the pieces could be fired and still absorb water and sweat, allowing for a wider selection of surface finishes.

By maintaining continuity, the geometry of the lattice transitions smoothly from one component to the next, this produces a structure without any corners or hard edges. For good daylighting, this type of continuity is important to eliminate any harsh transitions or sharp contrasts that can result in glare conditions and cause visual discomfort. By digitally modeling these geometries parametrically, difficult daylighting, shading, and internal gain conditions can be addressed relatively quickly through simulation based on real climate data from specific sites and locations; such as solar angles, cloud cover, and air quality. The depth of the structure, thickness of components, scale of openings, etc. can all be easily adjusted in the parametric model to design lattice structures for different desired performance results, where traditionally, an entire prototype would have to be produced and studied under correct lighting to design for such conditions. This reduces the need for a lot of physical testing, that would have previously been required for observing shadow patterns and resolve lighting issues. With new computational tools, difficult geometries and complicated structures can be effectively resolved digitally. This opens many opportunities for developing climate responsive strategies, sustainable design solutions, and new interesting and aesthetically pleasing geometries.

CONCLUSION

In regions with minimal access to energy resources and high-tech building systems, a blend of high-tech design methodologies

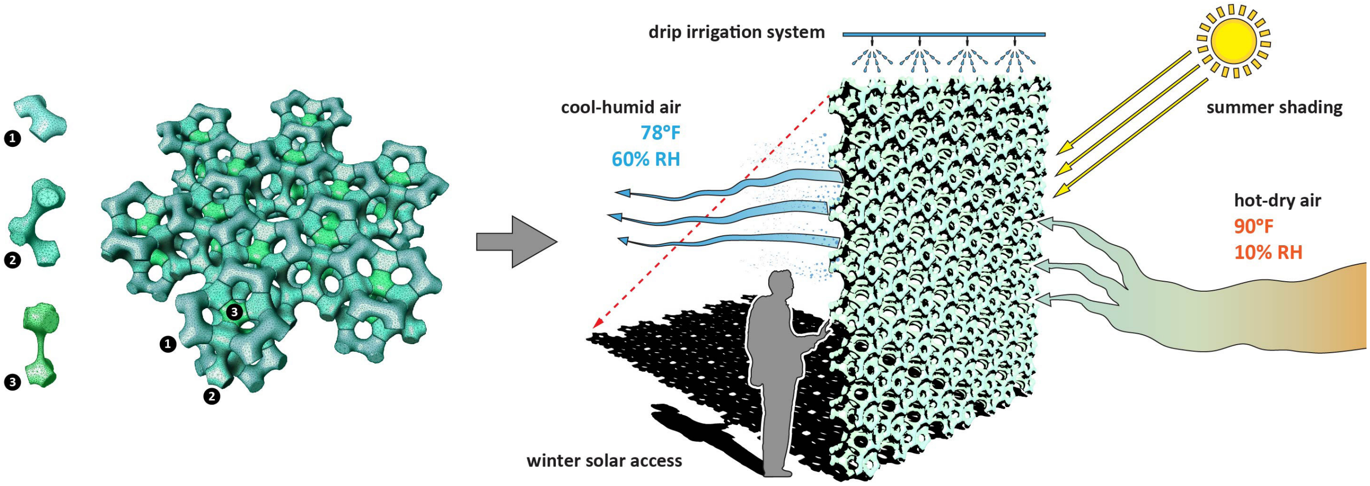

Figure 4: 3D packing geometry with three components (left), and climatic response as a ceramic lattice structure (right).

and low-tech bioclimatic strategies using simple materials and methods can produce effective solutions. Maintaining human comfort in remote sites requires taking advantage of natural and passive principles to control the thermal environment; such as, cross-ventilations, daylighting, and passive heat transfer. Climate control systems must respond to environmental loads in a distributed fashion at the building envelope, rather than relying on energy intensive centralized building systems. In order to meet these challenges, lattice and screen wall systems are effective tools, acting as buffers to environmental loads, allowing the architectural envelope to respond effectively to climate and environmental variability. Screen walls have been used effectively for thousands of years to naturally diffuse light, temper heat, and filtering air through architecture without requiring hermetically sealed building envelopes and mechanical systems, which are difficult to maintain in locations with scarce resources. Only recently because of the desire for sealed envelopes and air conditioning, have screen walls and open lattice structures been replaced with less complicated assemblies. Though they may have gone out of fashion, perforated wall systems remain highly effective as sustainable bioclimatic strategies for maintain thermal comfort. And presently, these systems are finding new life with the digital design and fabrication of environmentally responsive building systems, combining new and old manufacturing technologies to balance performance and practicality as the foundation for a new era of climate based design and sustainability centered on passive, decentralized environmental control systems.

ENDNOTES

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Figure 5: Slip cast, celadon glazed and fired structural members cast from 3D printed originals (top). Modular structure assembled from individual stoneware pieces (middle). Modular structure assembled from individual stoneware pieces (bottom).