3D PRINTED ARCHITECTURAL FACADES FOR CLIMATE ADAPTATION

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Abstract

This paper presents ongoing research into 3D printed clay ceramic assemblies as a locus for expanding architecture's ecological agency. The work has developed through academic research with architecture students at Tulane University and explores how techniques of additive manufacturing with clay can yield novel geometries and textures that open up new possibilities for a building facade to perform ecologically in relation to climate control, water management, and providing habitat for more-than-human species of plants and animals. Given that clay is a natural material in great abundance, its durability and weather resistance when fired, and its easy printability without generating any waste, it is a logical material to consider when thinking about decarbonization in construction. This research focuses specifically on how modular ceramic components can be designed, fabricated, and assembled to form larger systems of enclosure and habitation, reinterpreting traditional typologies of bricks, tiles, and shingles. The paper situates the work within the broader lineage of clay construction techniques, reviews precedents in 3D printed ceramics and the adaptation of this technology to the architectural scale, and discusses how digital techniques of design and robotic techniques of fabrication present an opportunity to meld traditional clay fabrication with computational workflows. The paper presents the pedagogical framework of the research and includes documentation of several student projects, which are explored via both speculative drawings and full-scale prototypes produced with clay 3D printers.

Keywords: Ceramics, Additive Manufacturing, Building Performance, Climate Adaptation

1 Introduction

Humans have been making buildings with clay for millennia. From the prehistoric wattle-and-daub structures of the Vinca people in the central Balkans to the hogan dwellings of the Navajo to the mud bricks of the Anatolian city Çatalhöyük, raw and sun-dried clay composites have played a critical role in the development of early civilizations and urban cultures (Staubach 2013, 112-123). Fired and baked clay components, from the baked bricks of the Babylonian ziggurats to the terracotta roof tiles developed in ancient Greece to the richly patterned mosaic tiles of Islamic architecture, brought even greater scale, structural durability, and ornamental possibility (Staubach 2013, 124-127; Campbell 2003). The ubiquity of clay ceramics persists in contemporary architecture, from standard, off-the-shelf tiles to the more complex and bespoke terracotta facade systems that take on increasingly complex approaches to building performance and ornamentation (Bechtold, Kane, and King 2015).

In recent years, as additive manufacturing (AM) technology has become more accessible and widespread, a number of architects and designers have experimented with methods of 3D printing clay to explore the potentials of mass customization to inform new approaches to spatial effect, ornamentation, and building performance. Building upon these important foundations, this paper presents ongoing research into 3D printed ceramic assemblies as a locus for expanding architecture's capacity to decarbonize and engage productively with broader ecological systems. The work has developed through academic research with architecture students at Tulane University and explores how techniques of AM with clay can yield novel geometries and textures that open up new possibilities for a building facade to perform ecologically in relation to climate control, water management, and providing habitat for more-than-human species of plants and animals. Given that clay is a natural material in great abundance, its durability and weather resistance when fired, and its easy printability without generating any waste, it is a logical material to consider when thinking about decarbonization in architectural materials. The research focuses specifically on how modular ceramic components can be designed, fabricated, and assembled to form larger systems of enclosure and habitation, reinterpreting traditional typologies of bricks, tiles, and shingles.

2 Background: Additive Manufacturing of Clay Ceramics and Ecological Performance

Extrusion-based 3D printing with clay ceramics is now a familiar focus of fabrication research in schools of architecture, as the relatively fast printing process and recyclability of the material make it an effective pedagogical tool for introducing students to techniques of AM. Early work in this area, such as the *GCODE.Clay* research by Ron Rael and Virginia San Fratello, focused primarily on the scale of the object or vessel, developing ways to custom program a robotic extruder to yield unexpected and richly patterned textures in the printed artifact (Rael and San Fratello 2017). It is only in recent years that architects have begun to scale up the technology to architectural applications akin to more traditionally fabricated terracotta rainscreen facades. Notable examples include the *Flora Field* architectural installation in St. Louis by Kelley Van Dyck Murphy (Ackerburg 2023) and two recently completed projects by StudioRAP in the Netherlands, *New Delft Blue* and *Ceramic House* (Ravenscroft 2023; Jackson 2023).

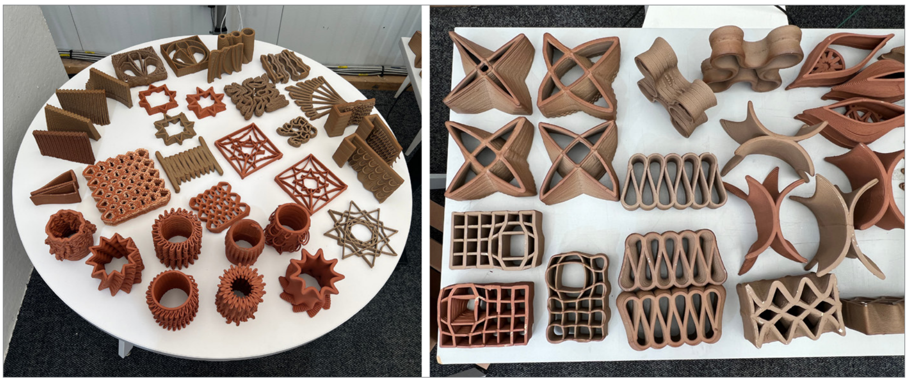

Figure 1. Initial 3d printed ceramic material studies and prototypes testing different techniques for toolpath design, texture, aperture, and modulation

While these projects demonstrate the rich textural and ornamental possibilities for 3D printed ceramics, several architectural researchers have been exploring the ecological possibilities of modular 3D printed ceramic systems. Recent work by op.AL utilizes multi-axis robotic extrusion to create volumetric ceramic modules that can vary to accommodate habitats for different plant species (Scelsa et al. 2023). This strategy demonstrates the possibility for mass customized modules to respond to different parameters related to habitat support. Research by an interdisciplinary team at Texas Tech University similarly explores the capacity for 3D printed ceramic modules to accommodate plant life, but their prototype incorporates a secondary module that promotes evaporative cooling (Rabb, Maher, and Hunt 2023). The design for this module collects excess water from the plant irrigation and takes advantage of the porosity of the 3D printed clay to facilitate airflow over these micro-reservoirs and the cooler temperatures that result as the water evaporates. The research presented in this paper builds upon these key precedents, testing ways to extend similar modes of ecological performance to the larger scale of a building facade.

3 Research and Pedagogical Methods

This work was developed in a spring research studio taught at Tulane University School of Architecture in spring 2024. The course, an advanced options studio for 4th year undergraduate architecture students (all of whom were new to both ceramics and advanced 3D printing workflows), introduced AM methods with robotic clay printers in the newly established Digital Ceramics Lab, a partnership with the Newcomb Art Department at Tulane. The intent was to develop a high degree of fluency with the tools at the scale of architectural facade components, while also developing larger ideas about the material's ecological performance through the design of a speculative building proposal. The first five weeks of the semester consisted of a series of short design and fabrication exercises introducing 3D printing workflows and acclimating the students to working with clay. Importantly, these exercises sidestep the conventional and most common methods of generating G-code (the textual language commonly used as instructions for 3D printers) that typically rely on standard slicing algorithms that cut horizontal, two-dimensional layers through a 3D digital model. Instead, the students learned methods of generating custom G-code through parametric models that allow them to develop controlled and iterative logics of form, geometry, and texture, understanding how slight modifications

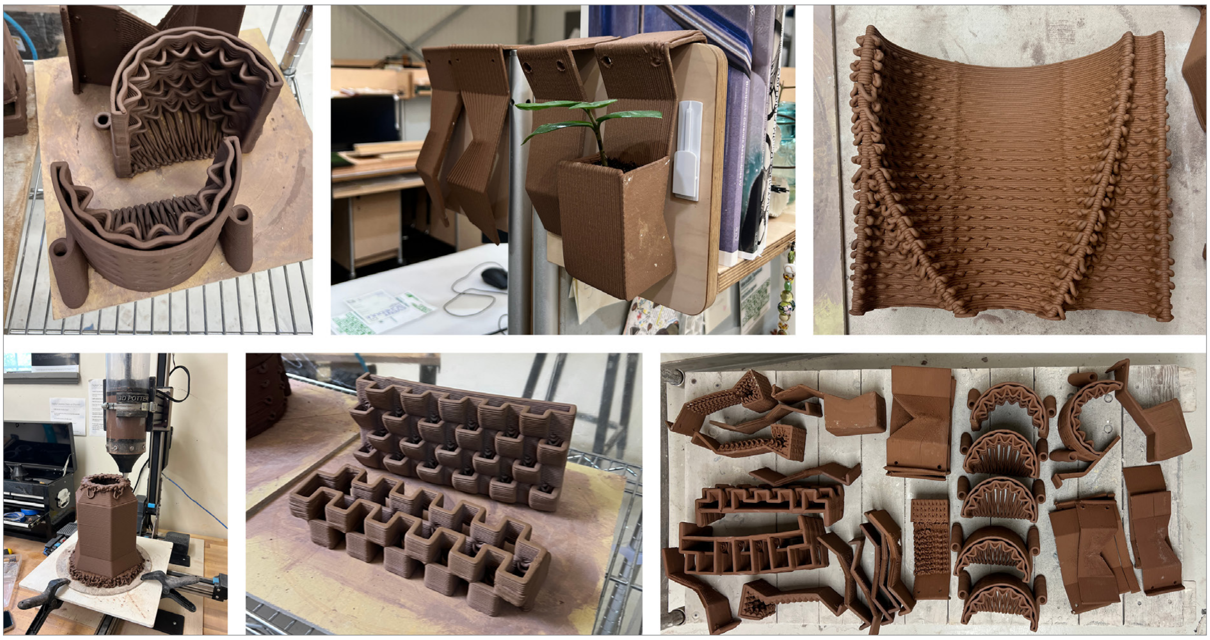

Figure 2. Studies integrating micro and meso scale research at the scale of the texture and module

in the toolpath of the extruder can produce dramatic effects at the scale of the texture or the module. These techniques were tested through three exercises focused on specific module typologies: a cylindrical vessel, a thick two-dimensional tile, and a stackable block (Figure 1).

These initial exercises informed the second project, a speculative design for a small residential building sited in New Orleans. The design projects developed through a scalar framework in which students were continuously working across three scales: the micro scale of the clay body and the novel textures that can be produced through careful calibration of the extrusion toolpath; the meso scale of the modular component and its logics of repetition and variation; and the macro scale of the entire assembly and its engagement with the surrounding ecosystem. Students, working in teams of two, began with initial speculations and prototypes testing how qualities at the micro scale, such as texture, aperture, or porosity, might produce new possibilities for bioreceptivity, water management, or thermal performance. This phase included a literature review of architectural material strategies related to these modes of performance, which helped each team focus on specific drivers for their project. Students integrated this research into iterative printed prototypes, testing forms and geometries for both aesthetic and functional possibilities (Figure 2), but also thinking about the pragmatics of modulation, attachment strategy, and how individual parts can be assembled into larger facade systems. In parallel with this work at the scale of the component, students began to develop sited proposals for small residential buildings in the Bywater neighborhood of New Orleans. The building served as a test scenario for how the facade systems could be deployed at scale, providing constraints of dimensionality and orientation that helped inform how students continued to develop the design of the ceramic components. The final presentations of the work reflected the multi-scalar workflow of the projects, including drawings of the building proposals, but also numerous ceramic prototypes and a full-scale facade mockup that demonstrated proof-of-concept in terms of fabrication feasibility and attachment strategy.

Figure 3. *Ceramic Wetland* (C. Kelley and S. Vladimir). Three types of ceramic modules (left) are designed to delay the flow of stormwater before it reaches the ground. The wall modules (center and right) integrate dense layers and scoops to detain water within the facade

4 Case Studies

A closer look at several projects from the studio's first iteration demonstrates the potential for this research to catalyze future development. *Ceramic Wetlands* proposes a building envelope consisting of ceramic modules designed to direct and slow rainwater before gently releasing it into a natural rain garden (Figure 3). The team developed module types for roof, wall, and ground paver applications, testing how controlled porosity and expanded surface area at multiple scales might help detain stormwater, a critical concern in cities like New Orleans that face regular flooding and stress upon municipal stormwater systems. The wall system consists of alternating ceramic modules suspended in a tensile grid, creating a cascade of roughly textured and contoured tiles that dramatically increases the envelope's surface area relative to a conventional flat wall. The AM process of fabrication uniquely enables the production of porous yet structurally stable modules that would not be feasible with conventional terracotta fabrication techniques.

Collective Meander revisits standard shingle facade construction through a new typology of ceramic shingles that can be deployed across the envelope according to different environmental and functional needs (Figure 4). The variable shingle system reinterprets conventional architectural elements such as the roof gutter, the cistern, and rainscreen facade cladding, incorporating these functionalities into the shingle itself. Like the previous project, the gutter and cistern shingles can slow, direct, and store stormwater, but the more solid shingles can also serve as a more conventional wall enclosure while also incorporating apertures at window openings. The use of AM in the fabrication of these shingles allows for a high degree of variation and customization as the parts address different exposures and performance requirements, which also yields subtle effects of filigree and gradation across the facade.

Vertical Understory proposes a series of structures clad with a system of porous, 3D printed ceramic modules that are optimized for both passive ventilation and plant habitat (Figure 5). The bricks incorporate variably sized apertures and pockets that are the unique result of this fabrication process; as

Figure 4. *Collective Meander* (S. Lindahl and D. Vorel). A simple shingle system includes multiple component types to serve different functions, such as providing apertures, serving as a gutter, and detaining stormwater (left). The full-scale mockup demonstrates the system's ability to accommodate a wide range of variation within its repetitive logic (center and right).

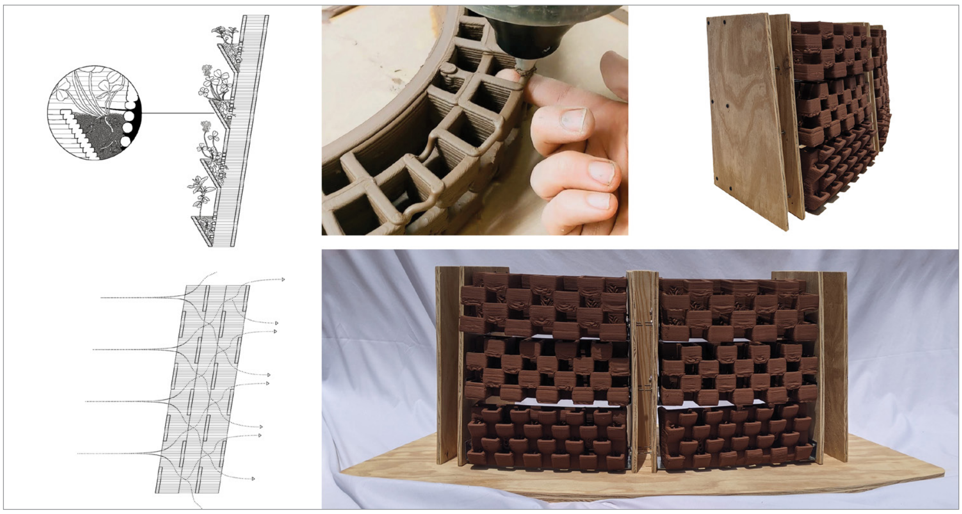

Figure 5. *Vertical Understory* (B. Cornett and K. Macumber). Stackable modules integrate pockets and apertures that allow for plant habitats and natural ventilation (left). The printing process requires temporary support of the cantilevers (top center), producing a range of pocket types in the full-scale mockup (bottom and top right).

cantilevers and openings are difficult to achieve with extrusion printing due to gravity acting on the bead of clay, the students developed a creative workflow of manually providing temporary support during the printing process. The integration of plants and apertures is intended to promote cooling through the process of evapotranspiration, by which plants remove moisture from humid air, thereby reducing the temperature. At the macro scale, the modules vary such that the larger pockets house larger plant species, while the more porous bricks are located adjacent to interior spaces to encourage passive ventilation through the envelope.

5 Reflections on the Work

Upon reflecting on this first iteration of the research studio, there are several areas for future development. For purposes of consistency and expediency, this studio used a single clay body (Cinco Rojo by Armadillo Clay), fired once to Cone 5 without glaze; alternative clay bodies and glazing techniques could bring even more ornamental and ecological potential to the work. While the student teams did execute successful full-scale mockups testing a range of different assembly techniques (tension systems, fasteners, clips), this dimension of the work would benefit from more development, perhaps with input from terracotta industry expertise to consider how AM components might be integrated into pre-existing, pre-engineered attachment systems.

The prototyping also validated the current limitations of AM for ceramic production at an architectural scale. Like many techniques of automated fabrication, 3D printing with clay (perhaps ironically) requires new and significant types of human labor to ensure success throughout the process. The bespoke nature of the process, combined with the idiosyncrasies of working with a fluid material like clay, is time- and labor-intensive relative to more standard techniques of architectural terracotta fabrication, such as extrusion, slip casting, or ram pressing. However, just as these earlier techniques were eventually scaled from artisanal settings to industrial factory production, it is reasonable to anticipate a near-future scenario of fully automated robotic fabrication for AM of architectural ceramic components. An additional challenge in scaling up this research would be to address potential concerns with how AM techniques might impact the propensity for ceramic components to crack when subject to freeze-thaw cycles in cold climates.

As a first step in a multi-year research initiative, this research studio yielded a range of successful proof-of-concept prototypes that demonstrate the potentials of designing, fabricating, and constructing facades with 3D printed ceramics. The proposals and prototypes successfully demonstrated geometric and material outcomes that would otherwise be impossible to produce with conventional fabrication processes. The studio also developed advanced, streamlined, and iterative workflows integrating design, production of G-code, and 3D printing, as well as a competency with the more analog and unpredictable processes of drying and firing that are critical aspects of ceramic production. As a research framework, the scalar approach of thinking in parallel at micro, meso, and macro scales proved effective as a way to foreground concerns of material, fabrication, and assembly in the design of a larger architectural project. As the impacts of climate change become more critical and more central to the practice of architecture, this work demonstrates how architects might reposition the building envelope as a much more active participant in modes of adaptation, both in the materials it is made of, and how those materials perform. 3D printed ceramic facade systems offer an alternative to more carbon-intensive materials like concrete and metal rainscreens. The technology's capacity to produce complex geometries and textures—and the ability to vary and customize these parameters based on specific functional and ecological performance criteria—presents significant opportunity to recast traditional ceramic and terracotta components as a critical strategy for climate adaptation.

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