Ceramic Morphologies
Precision and Control in Paste-Based Additive Manufacturing

ABSTRACT
Additive manufacturing technologies (AMTs), commonly referred to as 3D printing, are an emerging area of study for the production of architectural ceramic elements. AMTs allow architectural designers to break from established methods for designing with ceramic elements—a process where elements are typically confined to building components produced repetitively in automated settings by machine, die, or fixture. In this paper, we report a method for the design and additive manufacture of customized ceramic elements via paste-based extrusion. A novel digital workflow offered precise control of part design and generated manufacturing parameters such as toolpath geometry and machine code. The analysis of 3D scans of select elements provides an initial understanding of print fidelity. We discuss the current constraints of this process and identify several ongoing research trajectories generated because of this research.
INTRODUCTION
The contemporary interest in form customization of construction elements (Piroozfar and Piller 2013) has two primary motivations: a qualitative, design-driven desire for novel forms, or an aspiration for the quantitative improvement of building performance metrics (e.g., structural, thermal, or acoustic). However, producing customized construction elements, even within a digital (e.g., CNC technology-based) fabrication paradigm, remains technically challenging and is often cost-prohibitive. Additive manufacturing technologies (AMTs) are thought to be the all-disruptive technology to remove our current bias towards economies of scale and repetitive use of identical construction elements (Bechthold 2016).

However, significant obstacles remain. This research addresses three current shortcomings in paste-based AMT via the design and construction of a 3D-printed ceramic pavilion: the lack of integrated computational workflows that combine modularization and robot-ready tooling, the need for better data on material composition, and the quantitative assessment of production tolerances that currently limit the deployment of paste-based AMT in practice. A digital workflow for accuracy analysis was devised and tested on 19 construction modules, and the as-printed geometries were compared with FEA simulations to understand to what degree printing tolerances can be predicted.

BACKGROUND
AMTs have been explored at the architectural scale for nearly two decades. The process can produce unique elements with complex geometric features relatively quickly, without major fixed tooling costs. Multiple AMTs have been developed for clay-based ceramics at the scale of the architectural component, including powder (Sabin 2010) and paste-based methods (Friedman 2014).

This research focuses on paste-based extrusion, a technique mimicking a centuries-old coil-based technique utilized by potters. Research directed by Khoshnevis developed an early version called contour crafting. Here, a viscous bead of clay is deposited onto a flat surface and then smoothed by a trowel-like mechanism mounted behind the nozzle (Kwon 2002; Khoshnevis 2004). Several artists and architects have explored the formal possibilities afforded by paste-based ceramic AMT, yet little research exists for construction-scale applications that accommodate larger, modularized ceramic shapes (HKU 2017; IAAC 2017). No work has been published about integrated workflows for code production in a modularized 3D-printed system. Studies on computational workflows generally suggest that software is still the main barrier to digital fabrication (Mitchell and McCullough 1991; Landay 2009; Bechthold 2010; Braumann and Brell-Cokcan 2011).

Documentation on material composition is equally sporadic. No studies were found that assess the accuracy of design geometry relative to final 3D printed forms. Given the clear mandate of tight construction tolerances, this is a barrier for future implementation of paste-based 3D printed elements.

METHODS
3D-Printed Pavilion as Research Microcosm
We developed a prototypical pavilion, constructed at CEVISAMA 2017 in Valencia, Spain, designed to allow for the development of generalizable solutions to the shortcomings stated earlier (Figure 1).

Measuring 3 m tall, with a footprint of 3.2 x 3.6 m, the design consists of 552 unique elements measuring 260–545 mm in length and 70–150 mm in height. Elements were dry stacked and mechanically fastened to a steel frame, with a construction tolerance of 5 mm between pieces (Figure 2). The bumpy ceramic module form was derived to optimize heat exchange in naturally ventilated spaces. Using 19.84 km of extruded clay bead, 184 elements were produced in 358 hours of printing time, with an average bead cross-section of 1.8 x 8 mm (Figure 3).

Two platforms were used to 3D print prototype elements: a 6-axis robot (ABB IRB-4400) and a 3-axis 3D PotterBot with a build volume of 508(x) x 432(y) x 559(z) mm (3D PotterBot 7XL). Both systems use a commercially available, electro-mechanically actuated linear extruder, with a cartridge capacity of 2000 ml, resulting in a maximum toolpath length of 125,000 mm. The final elements were produced using the 3-axis machine. Porous, unglazed tiles used as the print bed facilitated component release (printed parts shrink significantly during drying) and provided a semi-rough printing surface to encourage bead adhesion. Early tests established approximate limits for surface slopes and identified process parameters (Table 1).

Elements were produced using a commercially available atomized clay mixture containing 42% quartz, 32% kaolinite, 13% calcite, 6% potassium feldspar, 3% sodium feldspar, and 1% dolomite, hydrated to 27% (±0.5%) using a deairing pug mill. Clay hardness was measured at 1.8-2.0 kg/cm² with a pocket-style penetrometer equipped with a 25 mm diameter plunger.
Ceramic module size, and ultimately the spacing of the pavilion’s support frame, were determined by print-bed dimensions and the maximum toolpath length achievable by a single cartridge of clay. During design development, these variables were digitally related such that a given pavilion modularization could be automatically evaluated in terms of printing platform or cartridge size requirements.

While components printed as single-layer shells without support geometry achieved the greatest material economy, the long unsupported spans generated with this method were highly unstable and prone to failure (Figure 4). Several studies tested methods for incorporating shell geometry and interior reinforcement strategy into a single continuous toolpath, culminating with a zigzag interior reinforcement strategy (Figures 5 and 6).

**RESULTS**

**Digital Design Strategy and Workflow**

A comprehensive parametric model was developed to control key aspects of the pavilion’s design and fabrication (Figure 7). The model not only generated the geometry of the ceramic elements and metal support frame, it also provided direct control of toolpath geometry and machine code generation. This functionality supported design adjustments until late in the development process and integrated all material and fabrication-specific parameters, including clay shrinkage rates after drying and firing and toolpath parameters for individual elements. Incorporating these controls into the digital workflow closely integrates global design geometry and element-specific toolpath characteristics. As a result, large-scale design shapes can be systematically discretized into construction elements for 3D printing, and design modifications can immediately be evaluated according to production limits (Figure 7, far right image). Though this integrated design and production approach is generalizable to many AMTs, an integrated means of breaking down a surface into construction modules is particularly useful in the case of ceramics, where production constraints such as kiln size often limit the size of construction elements.

<table>
<thead>
<tr>
<th>Table 1: Printing Parameters</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>Print Speed</td>
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<tr>
<td>Nozzle Diameter</td>
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<td>Layer Height</td>
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<td>Bead Width</td>
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Ceramic Morphologies: Seibold, Hinz, Garcia del Castillo, Martinez Alonso, Mhatre, Bechthold
We developed custom path-planning algorithms to generate the toolpath geometry described previously. Our algorithm contains features typically available from popular commercially available or open-source software, such as layer height and surface offsets, but is adapted for material-specific behavior, namely the need for a continuous spiraling toolpath that forms a single-layer shell with internal support walls for bracing. Incorporating toolpath and machine code generation directly into the parametric model provides the following: flexible control of commonly used parameters such as layer height, bead diameter, or brim offset; a rapid feedback loop for evaluation during the prototyping phase; reliable exchange data between the design and manufacturing teams; and a means of tracking printing progress during production.

3D Scanning and Analysis
The elements produced for the pavilion provide a dataset for evaluating the precision of the production process—an area critical to industrial production scenarios. Nineteen printed elements were 3D scanned using a structured light scanner (HP 3D Scan) (Figure 8). Elements were selected to provide a representative sample of the formal variations between the printed parts—such as slope, global curvature, and overall size. Deviations between design geometry and 3D scan data were then analyzed using the metrology software Geomagic Control X; a selection of deformation trends can be identified in Figures 9–11. Scan data reveals that 18.77% of design geometry was printed within a 1 mm tolerance, and that the maximum deviation per element averaged 15.75 mm. In addition to part-specific geometric characteristics, complex physical forces such as material plasticity, toolpath direction, layer compaction, extrusion pressure, and material composition dictate the behavior of elements while printing, as well as during the drying and firing process.

Simulation of Deformation During Printing
A linear finite element analysis model was created to predict deformation based on material self-weight and to provide data for comparison with the scanned elements. The comparison indicates that analysis based on gravity
9 Geometric deviation on the interior face of printed elements. Bump recesses and projections are less pronounced in printed elements than in design geometry. Thin, sloping flanges (see left edge of elements) exhibit the largest deformations, particularly on highly sloped elements. In this figure, elements are oriented as they were placed in the structure, though they were printed upside down to increase stability during printing.

10 The exterior, smooth faces of elements show consistent deformation behaviors: areas of high precision (green) are located near internal supports, while areas with the greatest bowing and deformation are located mid-span. Elements with higher slopes show larger deviations between areas of interior support geometry. In this figure, elements are oriented as they were placed in the structure, though they were printed upside down to increase stability during printing.

11 Element cross sections taken 5 mm below the top of each print show deformations along the smooth face of elements and diminished projections on the bumpy faces.
alone is insufficient to predict deformation during printing (Figure 12). A range of external forces (gravity, force of the printhead, adhesion to the printing bed) and internal tensions during drying and firing contribute to the final printed form.

DISCUSSION

Future Work
The design and realization of the pavilion revealed constraints and technical challenges related to extrusion-based ceramic 3D-printing technologies. Prints must be formed by a continuous toolpath, the length of which is limited by the capacity of the extrusion mechanism. Discrepancies between design geometry and printed components are caused by a variety of forces, both during the printing process and while the clay is drying or being fired. With these constraints in mind, we are investigating several areas of research:

- Material Delivery: We are currently developing an auger-based continuous extrusion system for a faster printing process. This system will reduce process time and increase the achievable size of printable elements.
- Geometric Fidelity: We are investigating processes including machine learning to compensate for deformations during printing. Three-dimensional scan data can be used as a training set with the printed toolpath as an input and the obtained deformation as an output. This model can be used for later prediction of printing toolpaths that automatically accommodate deformations.
- Functionally Graded Materials: We have developed custom tools and workflows for multi-material ceramic printing (Figure 13) and continue to research material additives that can be selectively introduced into a print to tune element performance.

CONCLUSION

Though ceramic elements have a long and varied history in architecture, certain forms remain difficult to produce. We demonstrate an integrated workflow for the customization of ceramic construction elements at the level of the individual unit using paste-based ceramic AMT. Material-specific design parameters and toolpath strategies can improve design outcomes, though current process-specific challenges have limited print size, geometry, and accuracy. Investigation into the design of the print material, material delivery system, and digital workflow could lessen some of these constraints, provide opportunities for geometric and material variation, and expand the application space of this process.
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NOTES

1. Print speed varied with extrusion rate.
2. Adjacent, coplanar toolpath geometries (e.g., zig-zag supports and exterior surface geometry) were separated by a 4mm gap.

REFERENCES


IMAGE CREDITS

Figures 3 and 6: © Fernando García del Castillo y López
All other drawings and images by the authors.

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