Ceramic Morphologies: Precision and Control in Paste-Based Additive Manufacturing

Conference Paper · October 2018
DOI: 10.52842/conf.acadia.2018.350

Ceramic Morphologies

Precision and Control in Paste-Based Additive Manufacturing

Zach Seibold
Material Processes + Systems Group, Harvard GSD

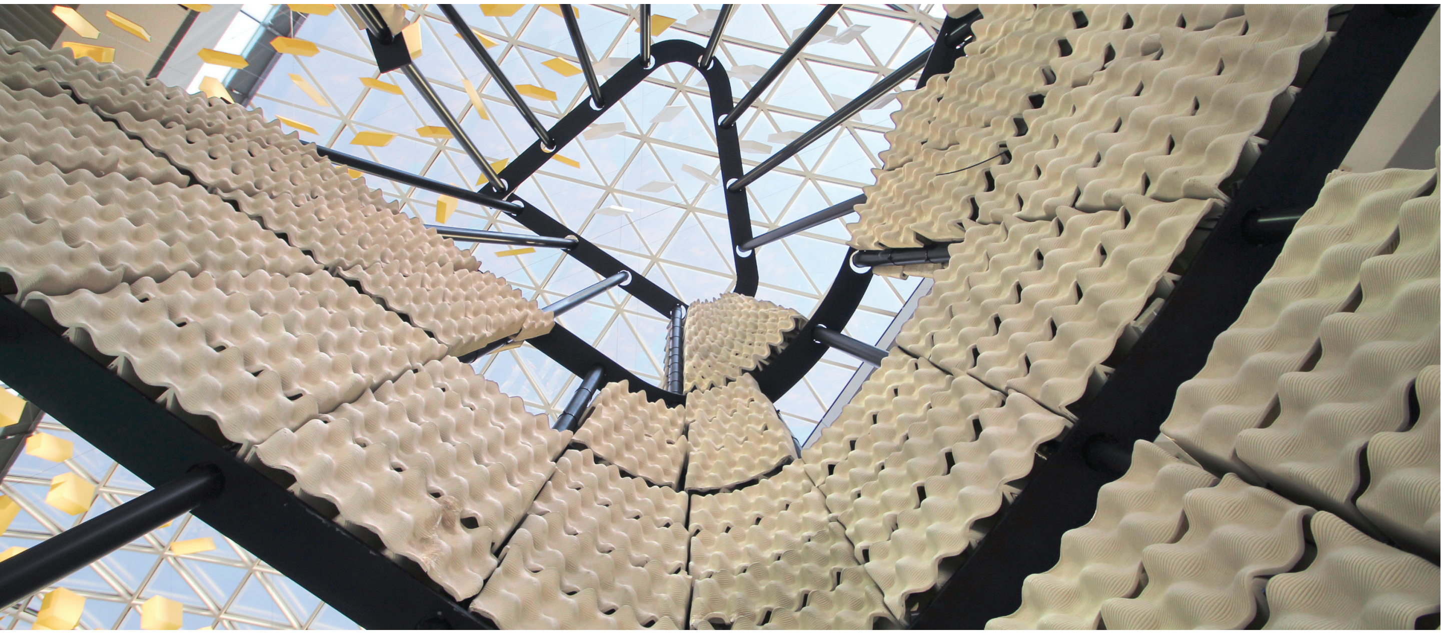
Kevin Hinz
Material Processes + Systems Group, Harvard GSD

Jose Luis García del Castillo y López
Material Processes + Systems Group, Harvard GSD

Nono Martínez Alonso
Material Processes + Systems Group, Harvard GSD

Saurabh Mhatre
Material Processes + Systems Group, Harvard GSD

Martin Bechthold
Material Processes + Systems Group, Harvard GSD



1

1 Photograph of pavilion interior.

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

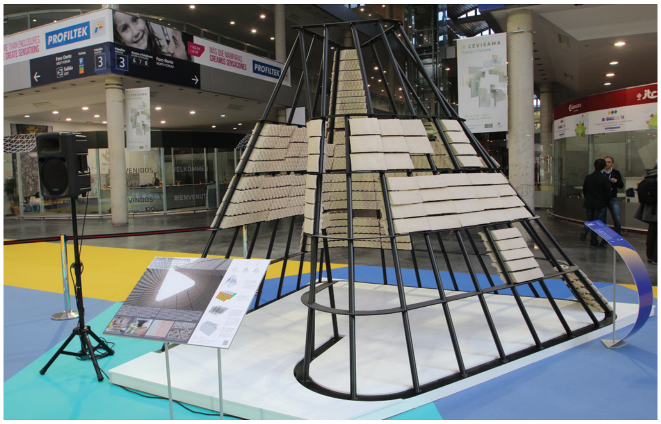
3D-Printed Pavilion as Research Microcosm

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).

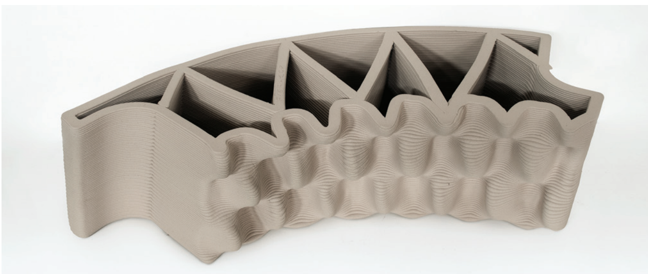
Measuring 3 m tall, with a footprint of 3.2 x 3.6 m, the design consists of 552 unique elements measuring 260–545 mm in length and 70–150 mm in height. Elements were dry stacked and mechanically fastened to a steel frame, with a construction tolerance of 5 mm between pieces (Figure 2). The bumpy ceramic 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, electromechanically 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).

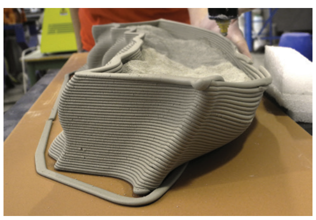
Elements were produced using a commercially available atomized clay mixture containing 42% quartz, 32% kaolinite, 13% calcite, 6% potassium feldspar, 3% sodium feldspar, and 1% dolomite, hydrated to 27% (±0.5%) using a deairing pug mill. Clay hardness was measured at 1.8-2.0 kg/cm^2 with a pocket-style penetrometer equipped with a 25 mm diameter plunger.



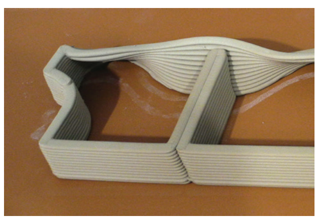
2



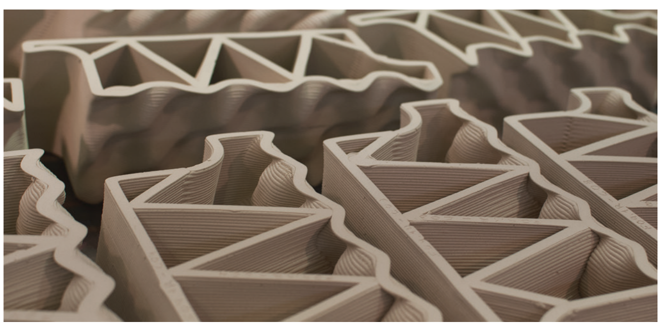
3



4



5



6

2 Photograph showing overview of prototype pavilion.

3 Photograph showing typical printed element.

4 Long unsupported spans were unpredictable.

5 Perpendicular supports provided balanced support, but created seams in an otherwise smooth surface and were subject to cracking due to the variable part thickness.

6 Zigzag supports provide an efficient means of creating a continuous path, and alternating layers run in opposite directions. To increase part stability during printing, the frequency of the supports could be adjusted when generating the toolpath.

Table 1: Printing Parameters

Parameter	Amount	Unit	Notes
Print Speed	15–30	mm/s	1
Nozzle Diameter	6	mm	
Layer Height	1.8	mm	
Bead Width	8	mm	2

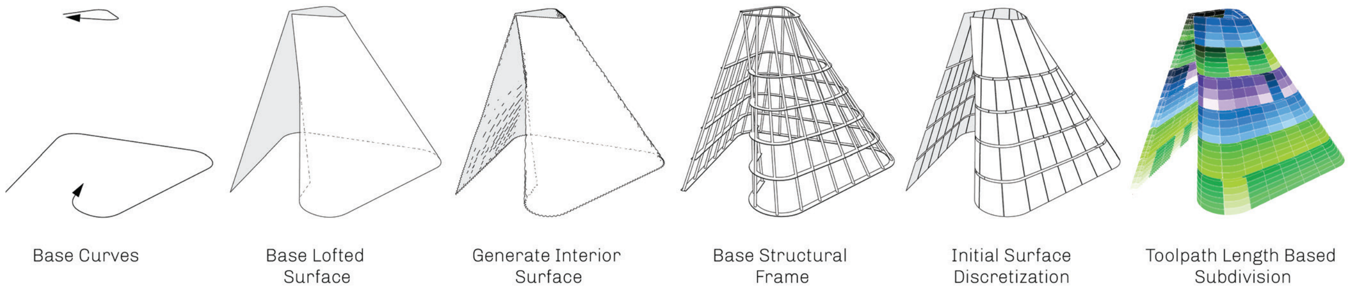
Ceramic module size, and ultimately the spacing of the pavilion's support frame, were determined by print-bed dimensions and the maximum toolpath length achievable by a single cartridge of clay. During design development, these variables were digitally related such that a given pavilion modularization 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).

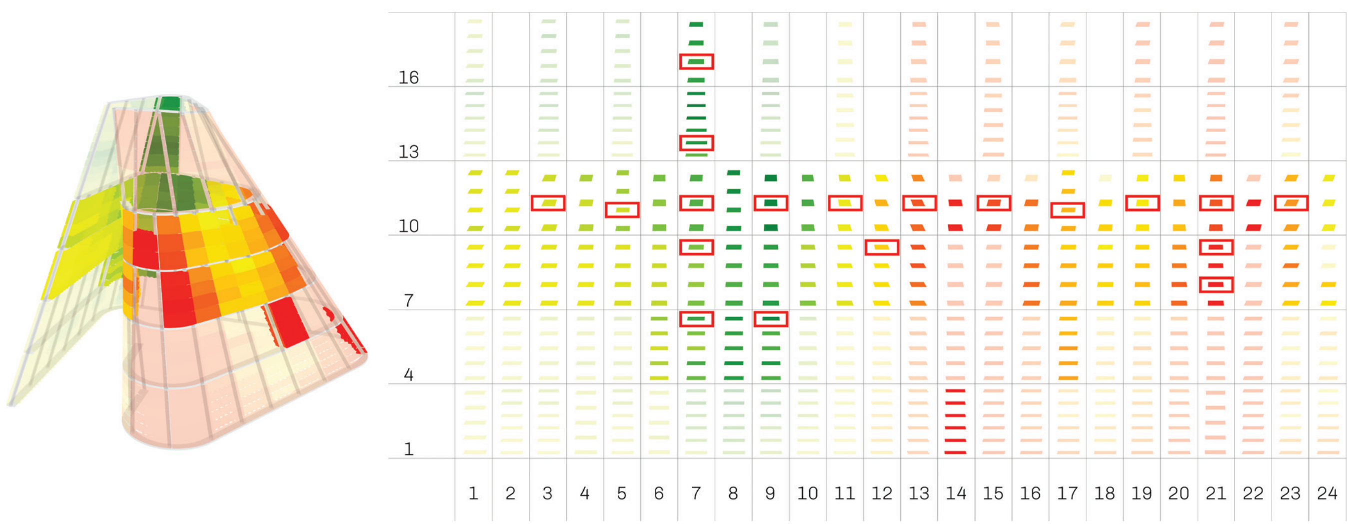
RESULTS

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.



7



8

7 The form generation process controlled by the parametric model. The toolpath length–based subdivision at far right indicates the number of elements per structural bay by color, and overall toolpath length by luminance.

8 The pavilion's ceramic elements. Colors indicate average element slopes, from 11° (green) to 28° (red). Printed elements are highlighted, while those that were 3D scanned are outlined in red.

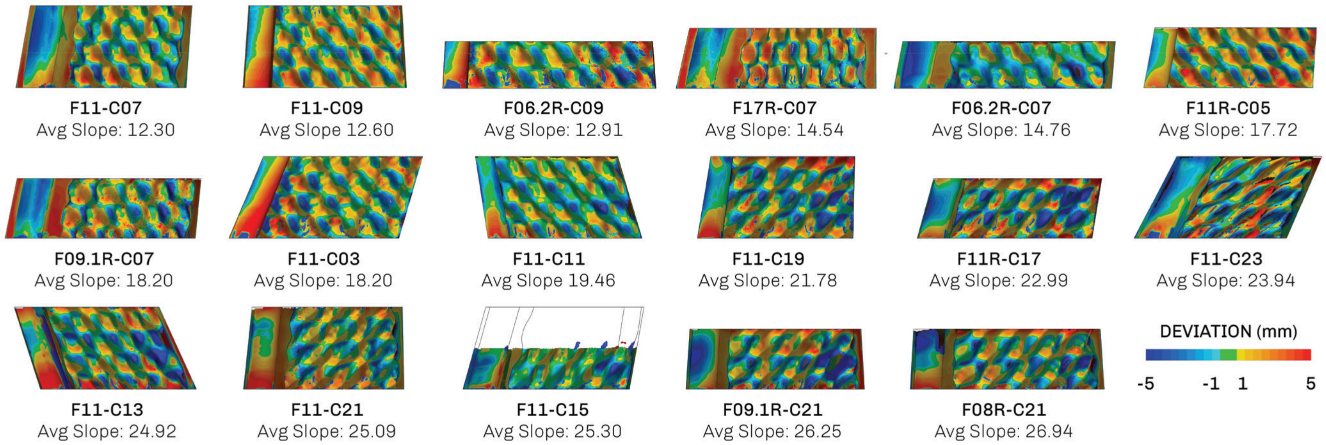
We developed custom path-planning algorithms to generate the toolpath geometry described previously. Our algorithm contains features typically available from popular commercially available or open-source software, such as layer height and surface offsets, but is adapted for material-specific behavior, 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

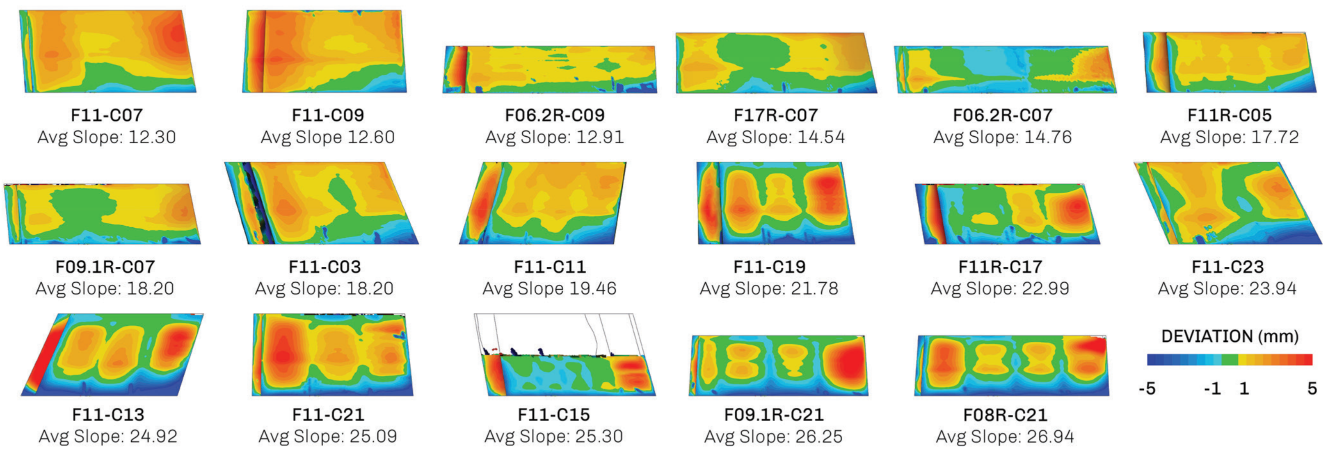
The elements produced for the pavilion provide a dataset for evaluating the precision of the production process—an area critical to industrial production scenarios. Nineteen printed elements were 3D scanned using a structured light scanner (HP 3D Scan) (Figure 8). Elements were selected to provide a 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

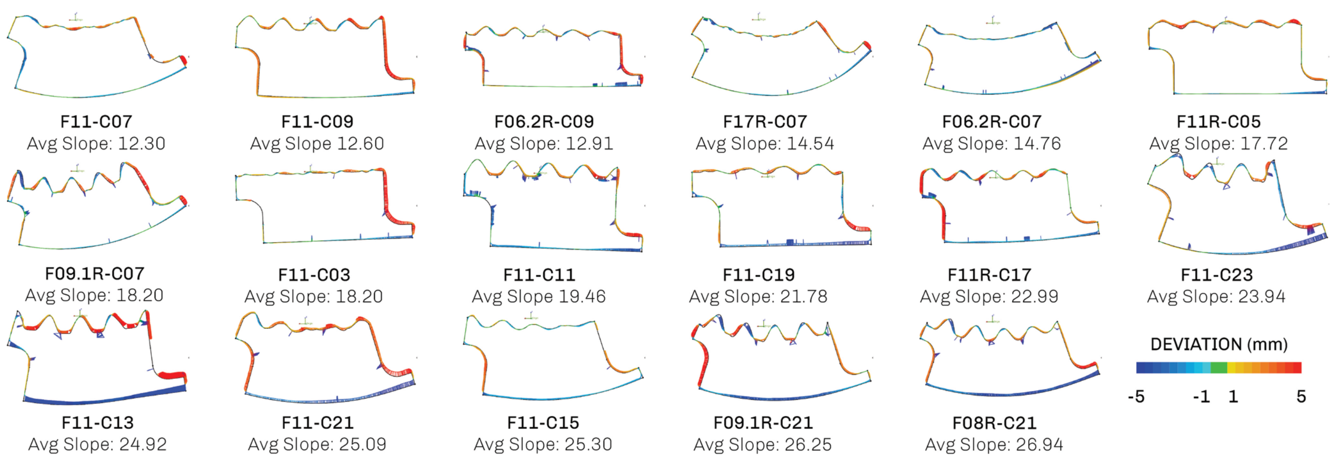
A linear finite element analysis model was created to predict deformation based on material self-weight and to provide data for comparison with the scanned elements. The comparison indicates that analysis based on gravity



9



10



11

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

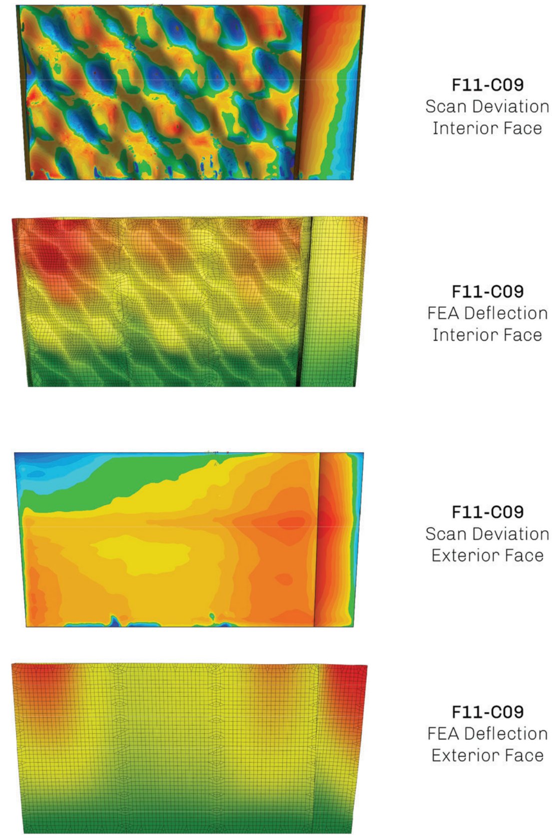
Future Work

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.



12

13

12 Image showing deflection values of a finite element analysis based on self-weight in comparison to the deformations exhibited by the corresponding 3D-scanned element. In this figure, elements are oriented as they were printed.

13 Early multi-material ceramic prints show promising results.

ACKNOWLEDGEMENTS

The authors thank ASCER Tile of Spain for their continuing support. Cevisama 2017 provided additional support for the exhibition. Javier Mira, Carmen Segarra Ferrando, Pilar Gómez Tena and Aroa Garcia Cobos from the Instituto de Tecnología Cerámica as well as Groupo on Market helped realize the design. We would also like to thank Fernando García del Castillo y López for his contribution in the 3D scanning of the printed ceramic elements.

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

3D PotterBot 7XL — DeltaBots. Accessed July 9, 2018. http://www.deltabots.com/products/3d-potterbot-35

Bechthold, Martin. 2010. "The Return of the Future: A Second Go at Robotic Construction." *Architectural Design* 80.4: 116–21.

———. 2016. "Ceramic Prototypes: Design, Computation, and Digital Fabrication." *Informes de La Construcción* 68 (544).

Braumann, Johannes, and Sigrid Brell-Cokcan. 2011. "Parametric Robot Control, Integrated CAD/CAM for Architectural Design." In *Integration Through Computation: Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture*, edited by by J. Taron, V. Parlac, B. Kolarevic, and J. Johnson, 242–51. Banff/Calgary, Canada: ACADIA.

Friedman, Jared, Olga Mesa, and Heamin Kim. 2014. "Woven Clay." In *Design Agency: Projects of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by D. Gerber, A. Huang, and J. Sanchez, 223–6. Los Angeles: ACADIA.

HKU. 2017. "Ceramic Constellation Pavilion | HKU Faculty of Architecture." http://www.arch.hku.hk/research_project/ceramic-constellation-pavilion/.

"HP 3D Scan | HP® Official Site." n.d. Accessed May 11, 2018. http://www8.hp.com/us/en/campaign/3Dscanner/overview.html#products.

IAAC. 2017. "TerraPerforma." Institute for Advanced Architecture of Catalonia. https://iaac.net/research-projects/large-scale-3d-printing/terraperforma/.

Khoshnevis, Behrokh. 2004. "Automated Construction by Contour Crafting—Related Robotics and Information Technologies." *Automation in Construction* 13: 5–19.

Kwon, Hongkyu. 2002. "Experimentation and Analysis of Contour Crafting (CC) Process Using Uncured Ceramic Materials." Ph.D. diss., University of Southern California.

Landay, James A. 2009. "Technical Perspective: Design Tools for the Rest of Us." *Communications of the ACM* 52 (12): 80.

Mitchell, William J., and Malcolm McCullough. 1991. *Digital Design Media: A Handbook for Architects and Design Professionals*. New York: John Wiley & Sons Inc.

Piroozfar, Poorang A.E., and Frank T. Piller, eds. 2013. *Mass Customisation and Personalisation in Architecture and Construction*. New York: Routledge.

Sabin, Jenny. 2010. "Digital Ceramics: Crafts-Based Media for Novel Material Expression & Information Mediation at the Architectural Scale." In In *LIFE in:formation, On Responsive Information and Variations in Architecture: Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by A. Sprecher, S. Yeshayahu, and P. Lorenzo-Eiroa, 174–82. New York: ACADIA.

IMAGE CREDITS

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

Zach Seibold is an architectural designer and Research Associate with the Material Processes and Systems Group at the Harvard Graduate School of Design. His research focuses on the impact that emerging fabrication techniques and material technologies can have on the production of architectural form. He holds a Bachelor of Architecture degree from Syracuse University and a Master of Design Studies with concentration in Technology from the Harvard University Graduate School of Design. Zach is also an adjunct faculty member at the Wentworth Institute of Technology, where he teaches courses in digital design and fabrication in the Department of Architecture.

Kevin Hinz was an independent contractor before earning a Master of Architecture from the Harvard GSD. His academic research explored applications for digital technology culminating in a Master's thesis proposal for 3D-printed ceramics relating theoretical and conceptual ideas to the process of design and engineering. This research continued at the Université de Montréal in the Department of Computer Science and Operations Research (LIGUM), where Kevin's expertise supported a new fablab built to research computational design, numerical simulation and model optimization for 3D-printed ceramics. Kevin now works as an architectural intern contributing to built work at the Swiss architecture firm EM2N.

Jose Luis García del Castillo y López is an architect, computational designer, and educator. His current research focuses on the development of digital frameworks that help democratize access to robotic technologies for designers and artists. Jose Luis is a registered architect, and holds a Master in Architectural Technological Innovation from Universidad de Sevilla and a Master of Design Studies in Technology from the Harvard University Graduate School of Design. He currently pursues his Doctor of Design degree at the Material Processing and Systems group at the Harvard Graduate School of Design, and works as Research Engineer in the Generative Design Team at Autodesk Inc.

Nono Martínez Alonso is an architect and computational designer with a penchant for simplicity. He focuses on the development of intuitive tools for designers and how the collaboration between human and artificial intelligences can enhance the design process. Nono holds a Master in Design Studies in Technology from the Harvard Graduate School of Design and works as a Software Engineer in the Generative Design Team at Autodesk Inc. Previously, he worked in the design and delivery of complex architectural geometries at award-winning firms, such as AR-MA and Foster + Partners. Nono interviews people on The Getting Simple Podcast to deconstruct how certain life habits can reduce the unnecessary complexities of our day-to-day.

Saurabh Mhatre is a Research Associate with the Material Processes and Systems Group (MaP+S) at the Harvard Graduate School of Design, where he graduated with distinction with a Masters in Design Technology. His interest lies in the synergy between design, technology and materiality. He is passionate about fabrication, robotics and photography.

Martin Bechthold—trained as an architect—is the Kumagai Professor of Architectural Technology at the Harvard Graduate School of Design, and Associate Faculty at the Wyss Institute for Biologically Inspired Engineering. He directs the Doctor of Design Program and co-directs the Master in Design Engineering (MDE) program. Bechthold is the founding director of the Materials Processes and Systems (MaP+S) Group. He collaborates with Allen Sayegh and Joanna Aizenberg in the context of the Adaptive Living Environments (ALivE) group where material scientists and designers work together to develop novel adaptive materials for applications in products and buildings.