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Extruded Tessellations: A novel structural ceramic system at the intersection of industrial ceramic extrusion and CNC fabrication

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Abstract

This research explores the customization potential of ceramic extrusion by means of integrating CNC fabrication tools into current industrial ceramic extrusion lines. In order to support this approach, we designed and built two wall prototypes made of 700 extruded ceramic pieces. The pieces were produced using a single extrusion die and were cut to custom lengths and angles using CNC disk cutters to produce a total of 38 unique pieces. We introduce the motivation behind our work, present a three-stage design workflow for the design of this type of ceramic system, and show our built prototype.

Keywords: Ceramic extrusion; CNC customization; Design workflow; Prototype; Tessellation.

INTRODUCTION

Ceramic is one of the oldest materials known to man. In fact, it is thought to be the first material system designed by humans (Bechthold et al. 2015). Notable for its structural and thermal properties, and its aesthetic versatility, ceramic has been the object of renewed interest in mainstream architecture in recent decades. New design and fabrication technologies have greatly expanded the formal potential and scope of application of this material, catalyzing this rediscovery (Bechthold 2016).

Today, an active area of research is the customization of ceramic building components. This is true both in industry and academia. For industry, the main effort has been on low-cost customization of ceramic tiles' surface appearance. In academia, the emphasis has been on the formal customization of construction components. A variety of production methods have been explored, including slip-casting (Weston, 2013) and form-pressing (Bechthold et al., 2013). However, no method has received as much attention as additive manufacturing technologies have (Khoshnevis, 2004; Seibold et al., 2018). In spite of academia's widespread interest in AMTs, this technology has not yet been embraced by the industry, mainly due to cost and precision limitations (Bechthold, 2016).

Our research takes another direction and explores the customization potential of ceramic extrusion, a different and comparatively underexplored production technique. Ceramic extrusion is the process where ceramic objects of fixed cross-sectional profile are produced by means of

Figure 1: Top row: examples of work in ceramics and digital design and fabrication done by the Material Processes and Systems Group at the Harvard Graduate School of Design. Left to right: Suspended Ceramic Shell (2014), Protoceramics (2015), Ceramic morphologies (2017), Ceramic Tile Grid Shell (2019), Ceramic Hypar Tower (2020), Bottom row: examples of work in ceramics and AMTs. Left to right: Woven Clay (2014), Spatial Print Trajectory (2019), Janus Printing (2019).

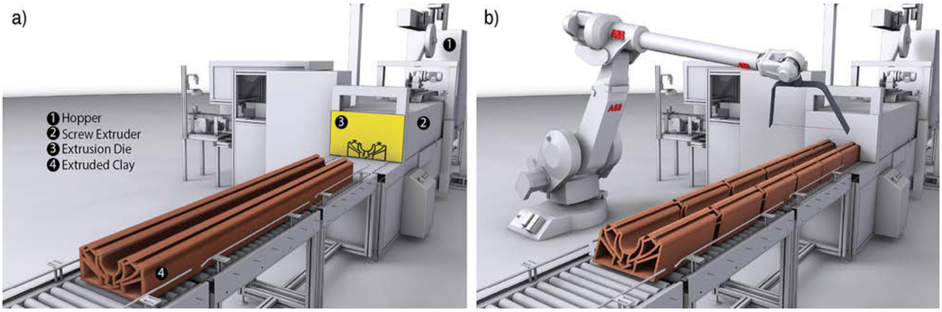

Figure 2: Left: Typical industrial ceramic extrusion setup. Right: Vision of the integration of a ceramic extrusion line with an industrial robot equipped with a wire cutter to customize individual components.

pushing clay through an extrusion die. A typical industrial ceramic extrusion line consists of a helical extruder that shoves clay through the die and a conveyor belt that receives the extruded clay (Händle, 2007). These pieces are then usually cut into smaller parts as needed. Ceramic extrusion allows for the creation of high quality, geometrically complex components at a competitive cost per unit in medium- to high-volume production (Bechthold, 2016).

One drawback of ceramic extrusion is that it does not lend itself easily to individual differentiation of the extruded components. Given that an extrusion die will impose a unique and continuous cross-section on the extruded element, the only possible variations to the component's geometry include bending the clay extrusion and cutting it into pieces at different lengths and/or cutting angles. In typical industrial settings, this customization can increase production costs proportionally to the amount of individually differentiated parts.

Our work explores the integration of CNC fabrication tools into current industrial production lines to overcome these limitations and exploit the possibilities inherent to ceramic extrusion. While some CNC capabilities such as automated disk cutting are part of many extrusion lines today, they are not typically employed in the customization of structural ceramic components. We describe our approach to achieving the above result in the following section.

METHODS

To assess the design possibilities latent in the integration of ceramic extrusion and CNC customization, we designed a structural ceramic system and tested it by building a wall prototype at a ceramics fair. This effort included the development of a three-stage design workflow to systematize the design of ceramic systems of this kind.

PROOF-OF-CONCEPT WALL PROTOTYPE

We set out to design a ceramic system based on a single component manufactured using a single extrusion die. We decided the component's cross-section —as opposed to its boundary surface— would be the locus to resolve most if not all the system's performative aspects. Furthermore, we determined that the ceramic system should maximize design effect and component variability while keeping production costs and logistical complexity to a minimum.

A THREE-STAGE DESIGN WORKFLOW

We created a parametric design model using Rhino Grasshopper (McNeel 2016) to efficiently design and test different components and wall assemblies. In this workflow, the design of the ceramic component is split into a three-stage iterative process. At each stage, we approach the design of the extrusion at both the component and the aggregation levels. We chose this approach to simultaneously address the individual component's design requirements and the effects that design decisions made on that level have on the aggregation's performance. Our process starts with the design of a simplified cross-section, continues with the refinement of the extrusion profile, and concludes with the CNC customization of each component, tying together design performance, material behavior and production constraints.

GEOMETRIC STAGE

The first step to design the ceramic extrusion is to produce a diagrammatic representation of the cross-section to be extruded —i.e. the component's base geometry. This simplified polygon broadly determines the component's behavior during production and the geometric rules for the aggregation of multiple modules. Because of our decision

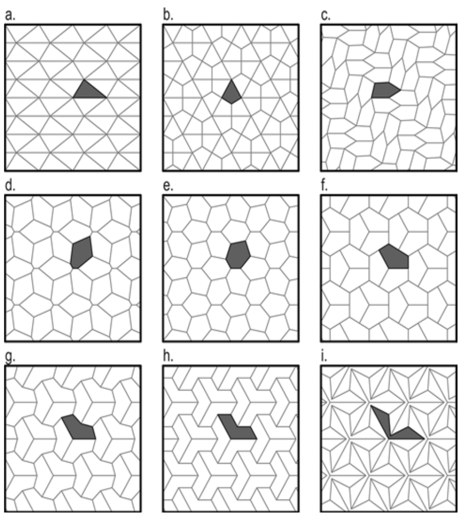

Figure 3: Different examples of monohedral tessellations: triangular (a); quadrilateral (b); pentagonal (c); hexagonal (d-i).

to use a single extrusion die, we used monohedral tessellations as the foundation for our base geometry.

In two-dimensional Euclidean geometry, a tessellation is the tiling of the plane using one or more geometric shapes, called tiles. A monohedral tessellation is a special type of tiling in which all tiles are the same shape and size. The fact that they can produce complex repeating patterns using a single base unit makes these tessellations relevant to the design of extruded ceramic components (fig.3). Strictly speaking, our base geometry is a polyrhomb that generates a rhombille tessellation. However, it can also be thought of as a concave hexagon that produces a hexagonal tiling, which is a better description design-wise.

When selecting the base geometry, we looked for specific attributes at the component and aggregation levels. At the component level, we looked for a tile with bilateral and rotational symmetry. The former results in more stability during extrusion while the latter maximizes the efficiency of the CNC cuts downstream. At the aggregation level, we prioritized tilings that had co-planar coincident sides —i.e. tilings where adjacent or nearby tiles have sides that are aligned on a straight line— and interlocking features.

Tessellations often present interlocking characteristics in which tiles are tightly coupled with their neighboring units. From a geometric standpoint, a tessellation can be said to be interlocking when no group of tiles (e.g. a row) can be moved on the plane of the tiling without affecting all the other tiles. Literature in masonry systems recognizes several types of interlocking between adjacent units, such as tongue and groove, dovetail, and geometry and stacking pattern (Ramamurthy and Nambiar, 2004). Our system falls within the last category. Interlocking tessellations may offer superior structural performance and reduce the need of bondage compared to non-interlocking tessellations (Dyskin et al., 2003). However, they may also result in intricate and time-consuming assembly sequences.

MATERIAL STAGE

After the component's base geometry is defined, its actual cross-section has to be designed. Doing so entails distributing material within the bounds of the base geometry to produce solid regions, voids, and other features on the unit's perimeter and interior substructure. These features will determine the component's performative capacities —structural, thermal, aesthetic, and so forth— and must simultaneously address material, manufacturing, and assembly constraints.

Before jumping into designing the component's interior substructure, the base geometry needs to be adjusted to compensate for ceramic shrinking. Clay shrinks during the drying and firing processes at a rate between 8–12% depending on the clay body's particle size and water content (Bechthold et al, 2015). Shrinkage works in two ways. First, the entire component shrinks uniformly until a given point, after which some areas continue shrinking, causing deformation in the component. This differential shrinking is more common in complexly shaped parts with unevenly distributed solid and void regions. Our design workflow addresses uniform shrinkage by upscaling the base geometry to produce an extrusion die larger than the desired final size of the component. The differential shrinkage, on the other hand, is counteracted by

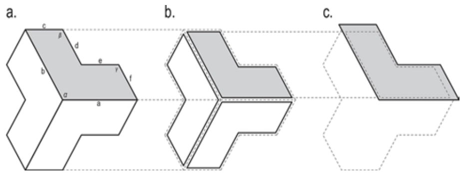

Figure 4: Adjustments made to the base geometery: a) original tile; b) interior offset to account for non-homogeneous shrinking; c) scaling operation to account for homogeneous shrinking.

incorporating a buffer distance between the components in the final aggregation. This is done by offsetting the component's outer perimeter (Fig. 4). It is important to note that offsets maintain angular but not dimensional relationships. This means that after the offset operation, the extrusion profile will not tessellate the plane if the tiles are aggregated in direct contact with each other.

From a mechanical standpoint, ceramic materials are brittle and lack tensile strength (Bechthold et al. 2015). The component's cross-section must account for these shortcomings. As a result, most non-solid ceramic extrusions will need some kind of interior substructure in order to be self-supporting.

The two most important parameters to consider when designing the component's interior substructure are the minimum wall thickness and maximum slab span. The former refers to the lowest possible cross-sectional width of the component's walls (both interior and exterior) while the latter refers to the distance the walls can span without needing additional supporting substructure. The mechanical properties of a ceramic material depend on the particular clay body employed and the circumstances surrounding the production of the ceramic part. Therefore, the component's minimum wall thickness and maximum slab span need to be determined in collaboration with a ceramic producer, who should also provide other relevant

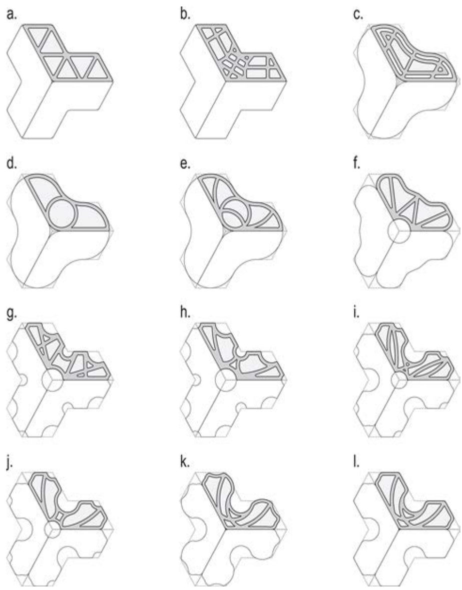

Figure 5: Different cross-section and substructure alternatives.

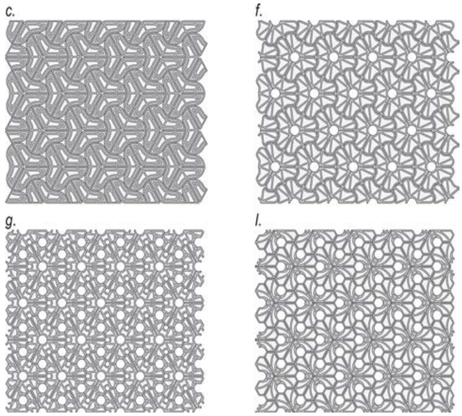

Figure 6: Tessellations resulting from the aggregation of different cross-sections. The characters in italic refer to the different component designs presented in Fig. 5.

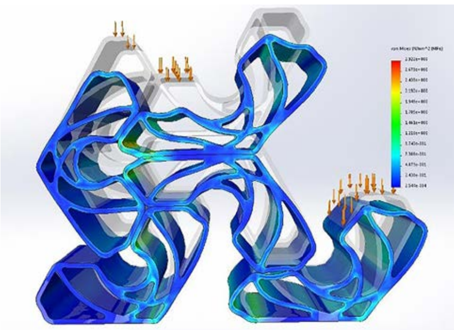

Figure 7: FE analysis of the component's performance at the aggregation level. The model includes modules in all possible orientations. Resulting stresses are well below material limits.

material parameters. In the case of our extrusion, the minimum wall thickness and the maximum slab span were 10mm and 200mm before shrinking, respectively.

Regarding the substructure design, our workflow allows us to operate at the unit scale and preview the results at the aggregation scale. Designing at these two levels is crucial given that monohedral tessellations often involve rotational transformations. This means that once they are assembled into a wall aggregation, the components will have different orientations and thus will be subject to different structural solicitations. Seeing the units assembled in their final orientation allows us to better understand this issue and visually assess the continuity of load transmission from unit to unit.

After evaluating different substructure design alternatives, we selected one (*l* in figures 5 and 6) and conducted a finite element analysis in Solidworks (Dassault Systemes, 2016). The analysis estimated the internal stresses in the ceramics from the wall's self-weight only. The study assumed a component weight of 14 kg based on density of ceramics of 2,300 kg/m3, and a wall height of 2.25m. Bending stresses were in the order of 3 MPa, well below even the lowest allowable bending stress of ceramics, which typically ranges from 15-25 MPa. Furthermore, the analysis aimed to determine how exactly the module's substructure was carrying the loads from unit to unit. The visual inspection described earlier is only referential; due to the formal complexity of the unit's substructure and the multiple orientations they adopt in space, understanding the system's structural behavior requires computational simulation. It is important to note that the component's substructure and overall cross-section also needs to provide stability during the extrusion process. This often requires creating additional substructure outside the base geometry, i.e. on the exterior of the component. The support structure is temporary and prevents deformations caused by self-weight while the clay is wet. It is removed after firing, and often leaves marks on the component's surface.

Another important aspect to consider in the cross-section design is the connections between adjacent components. This is particularly relevant when the ceramic system uses mechanical connectors, as opposed to mortar. In such cases, the cross-section may include formal features such as channels, notches or rails to work in tandem with the connectors. The fixation system must take into account the distance buffer between units described earlier. Tolerance errors will rapidly and unpredictably increase in this gap due to components' non-uniform deformations and the rotations involved in the assemblies. The fixation system needs to be designed with this issue in mind.

We designed a novel fixation system consisting of off-the-shelf plastic profiles and zip ties. The cross-section of the ceramic piece has six notches distributed across its perimeter. These notches correspond with the notches of the neighboring units such that a plastic profile can be inserted on the corresponding notches of adjacent units and tied together using a zip tie to produce a clamp-like mechanism. To deal with accumulated tolerance between pieces, we use neoprene padding that can be placed incrementally between adjacent units to compensate for larger or smaller dimensional errors. The fixation system was primarily informed by the need to quickly assemble and disassemble the structure, before and after the ceramics fair. In that regard, we followed general design for

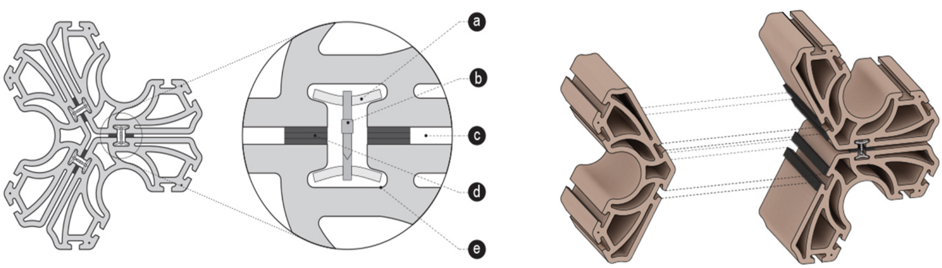

Figure 8: Fixation system detail: a) 80mm long and 2mm thick plastic profile with one perforation on each end; b) zip tie to secure the profiles; c) tolerance gap between components; d) neoprene strips for separation between modules; e) notch to insert the connectors.

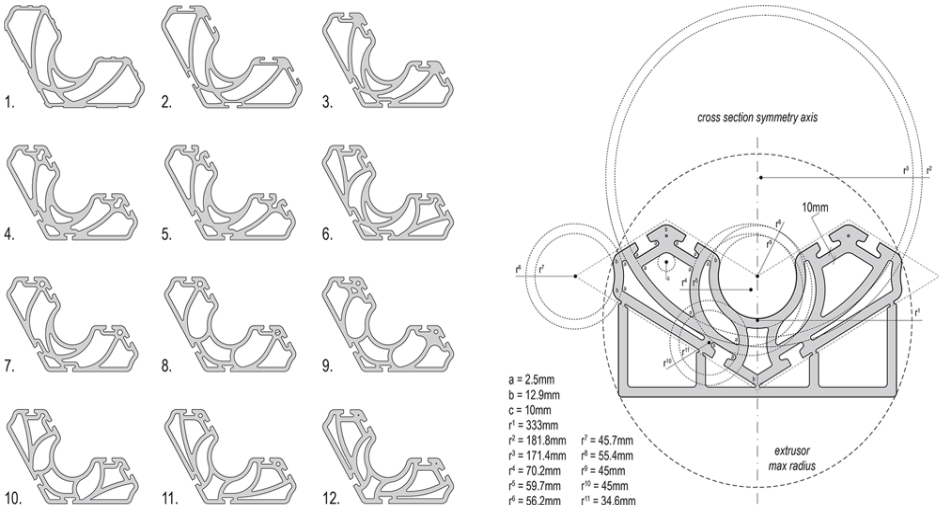

Figure 9: Left: Final iterations of the cross section design. Changes include small adjustments to the interior substructure (4, 6, 7, 10, 12), and sizing of the fixation notches (1, 2, 12). Right: Final component's cross section, in its extrusion orientation with support walls.

assembly and disassembly recommendations outlined in Boothroyd and Alting (1992).

CNC CUSTOMIZATION STAGE

The third and final stage in the extruded component's design involves customizing the different pieces to achieve a desired design and/or performative effect at the aggregation level. Our research identifies two possible technical implementations: using industrial robots equipped with wire cutters to cut the clay while it is still wet, and using CNC disk cutters to cut it once it has been fired. Robotic arms offer the greatest customization potential due to their degrees of freedom and the fact that the clay is still wet and malleable. However, they are not commonly used in industrial ceramic production today. CNC disk cutters, on the other hand, are not uncommon in industrial contexts and still offer great potential for component customization. Although using them makes the customization process more cumbersome and potentially more expensive, those concerns can be mitigated by making design decisions that make the most out of each cut.

To better understand all the above, our workflow lays out a basic taxonomy of cut types and draws connections between cutting operations at the unit, CNC, and aggregation spaces. The cutting-type taxonomy identifies three relevant dimensions. First, the geometry of the cut: cuts may be planar or ruled. Second, the effect of the cut on the component: cuts may either alter the shape of a component (e.g. length) or change its topology (e.g. exposing its inner substructure on its outer perimeter). And third, the purpose of the cut: cuts may add an aesthetic or performative effect at the aggregation level, or may change the aggregation logics of the system. Our component was customized with planar cuts that changed the shape of the units to produce an aesthetic effect in the walls.

Another aspect our workflow brings forth is the relationship between the ceramic extrusion, the CNC cutting space, and the unit at the aggregation level. Monohedral tilings often present rotational symmetry such that different units will have different orientations in space once they are part of the wall assembly. This means that three units placed with the same orientation on the CNC bed and cut with the same disk cutter angle will produce different surface angles on the aggregation space after being rotated along their longitudinal axis (figure 11 wall 1). Alternatively, different pieces can be placed in different orientations on the CNC bed and be cut using the same disk angle. If the piece

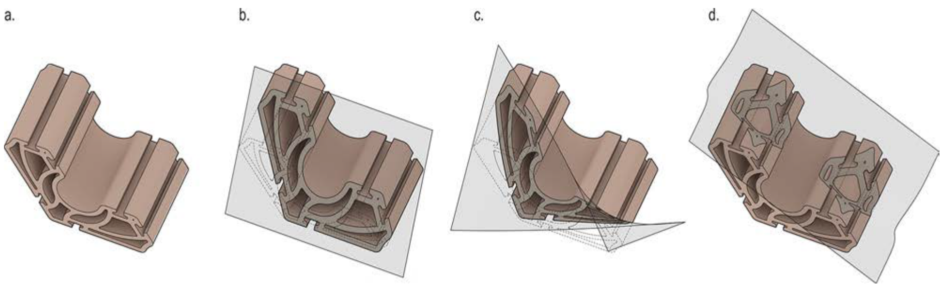

Figure 10: Examples of different cuts classified based on our cutting-type taxonomy: a) no cut; b) planar formal cut for performative effect; c) ruled planar cut for performative effect; d) ruled topological cut for performative effect.

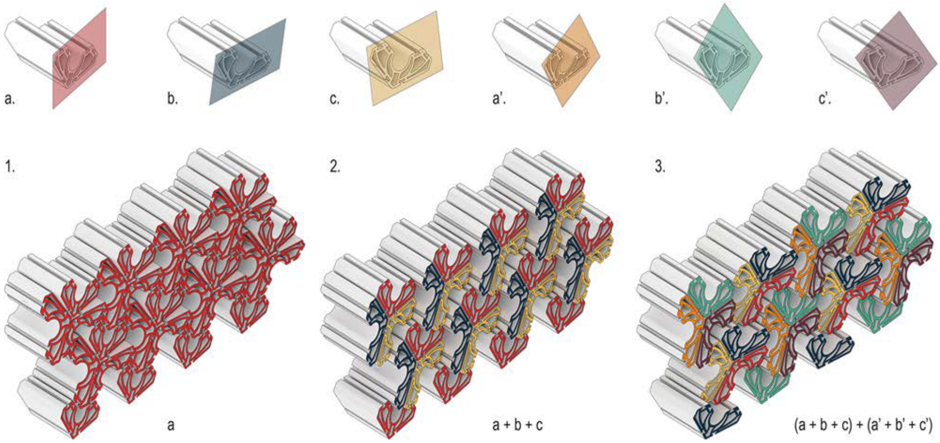

Figure 11: Diagram showing how a single cutting angle on the CNC space (either a robot or CNC disk cutter) can produce up to six different suface angles on the aggregation space in the case of a base geometry with a three-fold rotational symmetry. Pieces (a), (b), and (c) are cut in different orientations in space (120º rotation along longitudinal axis), while pieces a', b', and c', are the other half resulting from the cutting operation.

orientation on the CNC bed matches its final orientation in the wall assembly, the result is a co-planarity between adjacent units (figure 11 wall 2). Finally, a single cut can be used to produce two pieces (i.e. splitting a larger piece in half). This means that a single cutting angle in the CNC space becomes two surface angles on the aggregation space. Taken together, all the above means that a ceramic unit made from a tessellation with a three-fold rotational symmetry (such as ours), can be cut using a single disk-cutter angle to produce six different surface angles on the aggregation space (figure 11 wall 3). This minimizes the number of unique cutting operations and may result in lower production costs.

In our wall design, we followed the strategy above and combined it with cutting the pieces at different lengths to produce a staggered effect on the wall surface. Additionally, we left one of the component's sides flat for ease of transportation from factory to site.

RESULTS

We designed and built two ceramic wall prototypes made from 700 elements of 38 unique types. Wall A consisted of 350 pieces of 10 different types while wall B consisted of the same number of pieces of 28 different types (Fig. 12 and 13). The walls were 2.10m tall; the pieces ranged in length from 15-60cm and were cut in three different angles ranging from 15 to 25º for a total of 9 different orientations on the wall.

The walls were erected following a specific assembly sequence and the units were dry stacked and clipped together using perforated plastic profiles and zip ties. On top of each wall, a 5mm steel plate connected the top row of modules together using the same zip tie connectors employed in the rest of the wall. The steel bar acted as a beam, making the whole wall work together structurally.

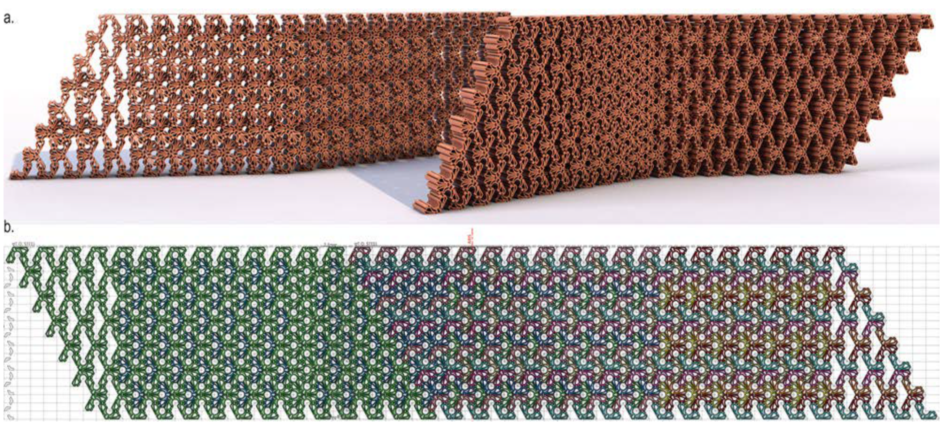

Figure 12: Top: Artistic rendering of our wall design. The two walls face each other, and are L-shaped to increase their stability. Bottom: Frontal elevation of the two walls. The different colors depict different unique pieces.

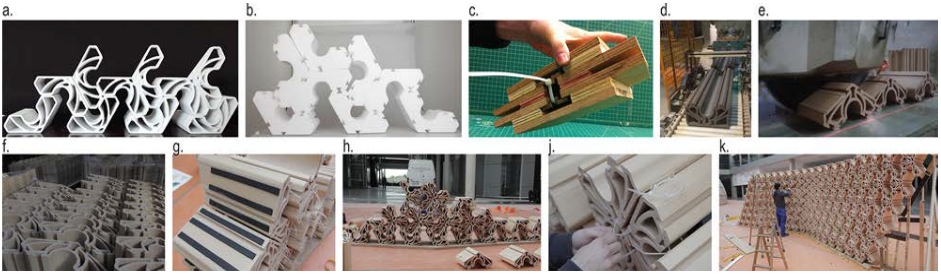

Figure 13: Series of images summarizing the design and production process of this project: a) initial formal explorations using 3d printed scaled blocks; b) test conducted by the contractor to evaluate our proposed connection system; c) our own initial test of the connector system —the image was used to communicate with the contractor overseas; d) component being extruded; e) component being cut with the CNC disk cutters; f) components being transported from factory to site; g) neoprene padding/separator; h) components being assembled; i) fastening of the zip tie connector; j) wall B almost finished.

DISCUSSION

There are two aspects of our work that we will unpack further in this section: the methods and tools used in the CNC customization process, and our design workflow and its implications for practice.

Regarding the first topic, the potential of using robotic tools to customize ceramic extrusions has been the focus of great work in recent years (e.g. Andreani and Bechthold, 2014, Schmidt, 2014). Much of that work was experimental in scope and did not involve real-world, industrial-scale production logistics, which are in turn crucial aspects in our project. Robotic tools have not been widely adopted in the ceramic industry and thus, using them in our research —situated in that context and directed towards that audience— did not seem justified. Furthermore, while CNC disk cutters and similar technologies are commonplace in industrial ceramic extrusion facilities, they are not regularly employed in the customization of ceramic components such as the one showcased here. One possible explanation is the increase in costs that these customization processes bring to the table, even when carried out by automated machines. The cost increase is caused by the difficult and time consuming additional machine and piece setup processes that automated customization entails —something often exacerbated by the industry's lack of know-how in this regard. Furthermore, designers and architects in academia and practice do not seem to push the industry in this direction either. This lack of interest may be partially explained by the belief that ceramic extrusions are limited and inherently difficult to customize, and by the complexities involved in their design, as shown in the methods section.

This last point connects to our second topic, namely the need for actionable knowledge, such as computational design tools and design guidelines and recommendations, to facilitate the design of structural ceramic extrusions. Our three-stage workflow, although limited, streamlines the extrusion's cross-section and wall assembly design processes. Each stage has a narrow design scope and deals with a well-defined number of design and technical considerations. This makes the task of designing the structural ceramic system structured and manageable yet flexible and generative.

Our work has several limitations. First, we did not exhaustively explore the CNC customization cut space described earlier. We believe there is great potential in topological cuts and in cutting operations that transform the assembly logics of the components. Second, the extruded units presented structural problems at weak points during transportation and handling. Having had the chance to test different cross-section designs (i.e. multiple die designs) would have helped; however, it was cost prohibitive in this

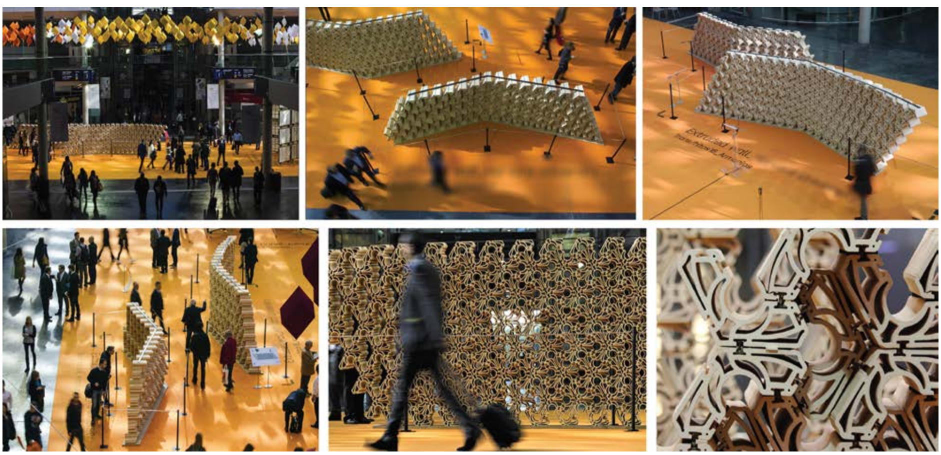

Figure 14: Photographs of the finalized wall prototype on site.

context. These are aspects of our design we will address in future work.

Finally, an interesting aspect of the project's design, construction and assembly process was that the design team and the manufacturer and contractor were in different countries and spoke different languages. This forced all actors involved to develop a shared language around these rather complicated geometries and entailed finding inventive ways to share knowledge about the novel ceramic system. In that regard, while this work was conducted pre-COVID, the problems arising from the geographical spread of the teams resonate with the challenges many design researchers face today to carry on their work.

FUTURE WORK

To continue this work, we plan to develop a computational design tool to fully streamline the design of this type of extruded component. Furthermore, we believe a set of formalized, actionable design guidelines that build upon our three-stage design workflow could be a long-lasting contribution to this research niche. As of now, our workflow does not take into account the whole breadth of design considerations that stem from the use of monohedral tessellations, nor does it comprehensively tackle the complexities of the cross-section design.

CONCLUSION

This project investigated the design space at the intersection of industrial ceramic extrusion and CNC fabrication. We used a single extrusion die to design a ceramic module able to produce planar, folding and curved wall assemblies that feature interlocking, ornamental patterns. The extrusions were cut at different lengths and angles using CNC disk cutters after the clay was fired, producing 700 pieces of 38 different types. These customized pieces were used to create a unique surface texture on every wall surface. The pieces were then dry stacked for ease of assembly and disassembly, using an ad-hoc mechanical connection made of off-the-shelf plastic profiles and zip ties. We outlined a three-stage design workflow where the extruded component was iteratively refined in three stages and at two different levels. We believe that the tessellated extruded wall succeeds in demonstrating the potential for the creation of novel structural systems at the intersection of industrial ceramic extrusion and CNC fabrication.

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REFERENCES

Alothman, S., Im, H. C., Jung, F., & Bechthold, M. (2019). Spatial Print Trajectory. In J. Willmann, P. Block, M. Hutter, K. Byrne, & T. Schork (Eds.), Robotic Fabrication in Architecture, Art and Design 2018 (pp. 167–180). Springer International Publishing. https://doi.org/10.1007/978-3-319-92294-2_13

Andreani, S., & Bechthold, M. (2014). [Re]volving Brick: Geometry and Performance Innovation in Ceramic Building Systems Through Design Robotics. In Gramazio F., Kohler M., & Langenberg S. (Authors), Fabricate 2014: Negotiating Design & Making (pp. 182-191). London: UCL Press. https://doi.org/10.2307/j.ctt1tp3c5w.26

Bechthold, M. (2016). Prototipos cerámicos – diseño, computación y fabricación digital. Informes de La Construcción, 68(544), 167. https://doi.org/10.3989/ic.15.170.m15

Bechthold, Martin, Kane, A., & King, N. (2015). Ceramic Material Systems: In Architecture and Interior Design. In Ceramic Material Systems. Birkhäuser. https://www.degruyter.com/view/title/301948

Bechthold, Martin, King, J., Kane, A., Niemasz, J., & Reinhart, C. (2011). Integrated Environmental Design and Robotic Fabrication Workflow for Ceramic Shading Systems. ISARC Proceedings, 70–75.

Boothroyd, G., & Alting, L. (1992). Design for Assembly and Disassembly. CIRP Annals, 41(2), 625–636. https://doi.org/10.1016/S0007-8506(07)63249-1

Ceramic Hypar Tower (2020). Retrieved from https://research.gsd.harvard.edu/maps/

Dyskin, A. V., Estrin, Y., Pasternak, E., Khor, H. C., & Kanel-Belov, A. J. (2003). Fracture Resistant Structures Based on Topological Interlocking with Non-planar Contacts. Advanced Engineering Materials, 5(3), 116–119. https://doi.org/10.1002/adem.200390016

Friedman, J., Kim, H., & Mesa, O. (2014). Experiments in additive clay depositions. In Robotic Fabrication in Architecture, Art and Design 2014 (pp. 261-272). Springer, Cham.

García del Castillo y López, J. L. B. (2019). Janus Printing. ACADIA 19: UBIQUITY AND AUTONOMY [Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]. Pp. 576-585. http://papers.cumincad.org/cgi-bin/works/paper/acadia19_576

Händle, F. (Ed.). (2007). Extrusion in Ceramics. Springer-Verlag. https://doi.org/10.1007/978-3-540-27102-4

Khoshnevis, B. (2004). Automated construction by contour crafting—Related robotics and information technologies. Automation in Construction, 13(1), 5–19. https://doi.org/10.1016/j.autcon.2003.08.012

Protoceramics (2015). Retrieved from https://research.gsd.harvard.edu/maps/

Ramamurthy, K., & Nambiar, E. K. K. (2004). Accelerated masonry construction review and future prospects. Progress in Structural Engineering and Materials, 6(1), 1–9. https://doi.org/10.1002/pse.162

Schmidt, P. (2014). Architect manufacturer collaboration through the design of a ruled surface cutter for extruded terracotta (Order No. 1566983). Available from ProQuest Dissertations & Theses Global. (1627753367). Retrieved from http://search.proquest.com/docview/1627753367

Seibold, Z. H. (2018). Ceramic Morphologies. Precision and control in paste-based additive manufacturing. ACADIA // 2018: Recalibration. On Imprecision and Infidelity. [Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]. Pp. 350-357. http://papers.cumincad.org/cgi-bin/works/paper/acadia18_350

Seibold, Z., Mesa, O., Stavric, M., & Bechthold, M. (2018, July). Ceramic Tectonics: Tile Grid Shell. In Proceedings of IASS Annual Symposia (Vol. 2018, No. 8, pp. 1-8). International Association for Shell and Spatial Structures (IASS)

Suspended Ceramic Shell (2014). Retrieved from https://research.gsd.harvard.edu/maps