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Ceramic Prototypes – Design, Computation, and Digital Fabrication

Prototipos cerámicos – diseño, computación y fabricación digital

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ABSTRACT

Research in ceramic material systems at Harvard University has introduced a range of novel applications which combine digital manufacturing technologies and robotics with imaginative design and engineering methods. Prototypes showcase the new performative qualities of ceramics and the integration of this material in today's construction culture. Work ranges from daylight control systems to structural applications and a robotic tile placement system. Emphasis is on integrating novel technologies with tried and true manufacturing methods. The paper describes two distinct studies – one on 3D printing of ceramics, the other on structural use of large format thin tiles.

Keywords: 3D Printing; Adjustable Mold; Structural Tile: Cold-Bending.

RESUMEN

Las investigaciones de la Universidad de Harvard en sistemas de material cerámico han introducido una gama de aplicaciones novedosas que combinan tecnologías de fabricación digital y robótica con diseños imaginativos y métodos de ingeniería. Los prototipos muestran las nuevas prestaciones de la cerámica y la integración de este material en la cultura de la construcción actual. Los trabajos van desde sistemas de control de luz natural a aplicaciones estructurales y un sistema de colocación de tejas robóticas. Se hace hincapié en la integración de nuevas tecnologías con métodos de fabricación probados y reales. El documento describe dos estudios distintos: uno sobre la impresión 3D de cerámica y el otro sobre el uso estructural de baldosas delgadas de gran formato.

Palabras clave: *Impresión 3D; moldes ajustables; baldosas estructurales; doblado en frío.*

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1. INTRODUCTION

The need to design, fabricate and construct one-of-a-kind buildings is as old as construction activity itself. Despite advances we continue to struggle with high production and construction costs when customizing building components. In the pre-industrial age craftspeople could readily create individualized elements based on their intimate knowledge of tools and materials, but their imagination was culturally and geographically limited and design expressions remained narrowly defined. During the industrialization the logics of scaled-up production systems all but eliminated the ability to individualize construction elements beyond merely configuring standard products. Monotony and repetition of identical units that represent the logics of economies of scale more than those of design continue to dominate today. But the rise of computational tools, and the ease with which computational models can translate into instructions for CNC machines and robotic manipulators has provided the conditions for now revisiting the old question of individualization. Current architectural design paradigms rely on customized components (1). This trend has been facilitated and enforced by the designer's global exposure to highly differentiated design expressions. Architects and owners are ever more compelled to lend their projects unique expressions and site-specific performance characteristics, yet costs remain a severe limitation. What role can ceramic systems play in this dilemma?

The ceramic industry consists largely of volume producers that output vast quantities of tiles for global markets. Over the past decades progress in material science and production engineering has led to significant advances in quality and productivity (2). The use of digital tools in design and production has further contributed to this development (3). Many of the large producers have implemented robotic systems in packaging or in glazing. These efforts succeeded in improving productivity and quality but they did not address the need to customize the product itself (4). Recently, however, even such high-volume production settings have undergone a change, in part through the integration of technologies such as digital ink-jet printing (5). These sophisticated systems enable intriguing aesthetic opportunities for surface and glaze effects, and, more importantly, they greatly facilitate the production of customized surface finishes. In doing so they are moving volume producer closer to the needs of the markets, and allow mass-producers to become mass-customizers by having specific tile designs be produced for a single project (6).

Digital ink jet printing can create unique surface qualities, albeit only for flat tiles. Architects are now rediscovering their interested in three-dimensionally complex designs of ceramic elements for façades, roofs and other areas, thus moving beyond planar surfaces covered with dry pressed or extruded ceramic tile (7). Design, production and construction expertise for these more complex systems remains underdeveloped, and very few specialty producers are currently able to meet the demands. These spatially complex ceramic systems and their related customization strategies have been the focus of research by Harvard University's Material Processes and Systems Group (MaP+S), directed by the author.

MaP+S investigates the intersection of robotics and ceramics, thus combining one of mankind's oldest material systems with the latest in fabrication and design technology. The work is interested in systemic solutions that are replicable rather than representing one-off instances of designs. Past studies have included integrated workflows for environmental design to production of custom shading lamellas (8) and robotic mosaic tiling (9). Ongoing studies include research into structural applications of thin ceramics, as well as the integration of robotic wire cutting into production lines for industrial extrusion (10). This paper discusses MaP+S work in additive manufacturing of ceramics, as well as the investigation into structural applications of thin, large-format tiles.

2. ADDITIVE MANUFACTURING METHODS FOR CERAMIC PRODUCTION

Additive Manufacturing Techniques (AMT) in architecture, commonly referred to as 3D printing, have been under development for approximately 15 years. The interest in this technology originates primarily in the ability to create geometrically complex parts as one-offs relatively fast and without major fixed tooling costs. Early work in ceramics was conducted by or under the supervision of Koshnevis (11). The group developed an approach called contour crafting, whereby a gantry or other mechanism is used to deposit relatively viscous clay in beads onto a flat base surface. The resulting contoured deposition is then smoothened by a small, proprietary spatula that is mounted immediately behind the material deposition nozzle. The process is similar to hand-building techniques used by potters for thousands of years, but it adds speed and digital controls as well as a host of features to control the consistency and quality of the clay body. Research by the contour crafting group switched to concrete soon after the initial study in clay, with the focus being on-site use of additive manufacturing in order to simplify construction logistics. Other work in 3D printing of technical and clay-based ceramics has focused on producing smaller objects (12). Commercial services are available to print small ceramic pieces by selectively solidifying a fine granular ceramic powder using commercially available 3D printer. These capabilities have attracted a small community of makers and artists that often produce relatively small artifacts with intricate geometries, or using designs highly driven by generative computational methods (13). Little recent work has been undertaken in printing architectural components in clay. The following sections describe related research underway at Harvard's Material Processes and Systems (MaP+S) Group.

2.1. Printed Clay: Micro-Extrusion

Earlier work by researchers at Harvard's MaP+S group developed an integrated workflow for ceramic 3D printing on the basis of a micro-extrusion technology developed by the group[1]. The underlying assumption was that exterior shading lamella often needed to be customized to adapt to overall façade geometries, satisfy desired shading parameters as well as match aesthetic preferences (Figure 1). The combination of these requirements can create a need for curved and

[1] At the time of the project the name of the group was 'Design Robotics Group (DRG)', which later changed into the current MaP+S. Nathan King and Christoph Reinhart were key collaborators in this project. Others involved include Anthony Kane and Justin Lavallee.

twisted shading lamella for which current production methods are prohibitively costly. Currently industrial producers would typically extrude flat and often hollow clay elements that are then cut to the correct size with an adjustment for shrinkage. The wet elements can then be slumped over fixed surface molds which are typically built out of wood, plaster, or CNC-cut foam. A separate mold would be needed for each individual element – a costly and time consuming approach. After drying to the green state the curved, hardened elements are kiln-fired.

The research developed an environmental design tool for shading design of exterior shading louvers which connected seamlessly to other modules geared to support design for construction activities and a newly developed robotic 3D printing system. The resulting integrated workflow reduced the design time for configuring individualized shading lamella by avoiding the costly and error-prone switching between software environments. An earlier publication describes the workflow itself, without however providing details on the 3D printing aspects (8).

The additive printing process of a relatively wet clay body was prototypical in nature, but still allowed substantial understanding to be developed on opportunities and constraints of this novel manufacturing method. The extrusion system consisted of a single-cylinder piston with a geared, variable speed electro-mechanical drive. Mounted to a 6-axis robot (ARB-4400) the extruder included a conical mouthpiece, milled out of solid aluminum, which formed a 25 mm diameter bead of clay when activating the piston (Figure 2). Beads of clay were extruded with a step-overs of approximately 20 -30 mm, resulting in a relatively rough surface finish with millimeter-size scallops and other features. The edges of the printed piece featured surface scallops that were similar to those found the 3D printing of concrete (14).

2.2. Support Strategies – Modular Mold

The clay mix used during the prototypical 3D extrusion process was relatively wet and needed to be fully supported while drying to a green state. Industrial producers normally use a plaster or foam mold when casting or slumping clay components. Instead of relying on these types of fixed geometry molds the researchers designed and built a modular, adjustable mold system at low cost. Adjustable molds are typically based on arraying a series of closely based pins that are individually actuated (Figure 3). A desired surface shape can be approximated by positioning each pin such that its head it tangential to the surface. An interpolator sheet is often placed to bridge the inevitable gap between pin heads. The molds made by the research team features 5 mm diameter pins spaced 25 mm apart.

The mold system, developed by Harvard's MaP+S researchers, features individual steel pins positioned in a series of perforated plates. A lateral shearing motion of the middle plate locks the pins in place after the robotic manipulator easily positions

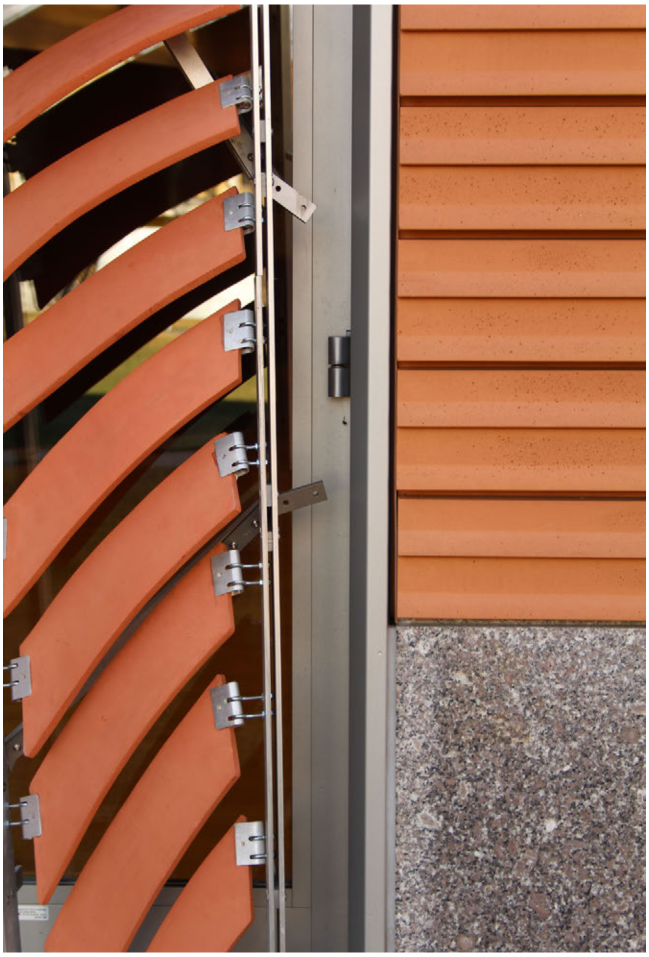

Figure 1. Prototype of individualized shading lamella next to an industrially produced ventilated façade using extrusions.

Figure 2. 3D printing test over a plaster mold.

each pin. Configuring the mold using an industrial robot takes only minutes for a set of 100 pins, thus is rather cost-effective. The mold system is modular. A limited number of adjustable mold modules can produce elongated forms as well as those approaching a square. This reduces fixed costs for mold tooling and expands the range of production options (Figure 4).

With more development time the quality of the robotic extrusion can be much improved. Simply dragging a blade after the nozzle would significantly reduce the resulting surface scallops (Figure 5). Contours could be precisely scribed with a pin while the clay is still wet. The relatively long drying time of a robotically extruded wet clay body presents a potential production bottleneck in production especially when compared to faster processes such as casting concrete over a similar mold.

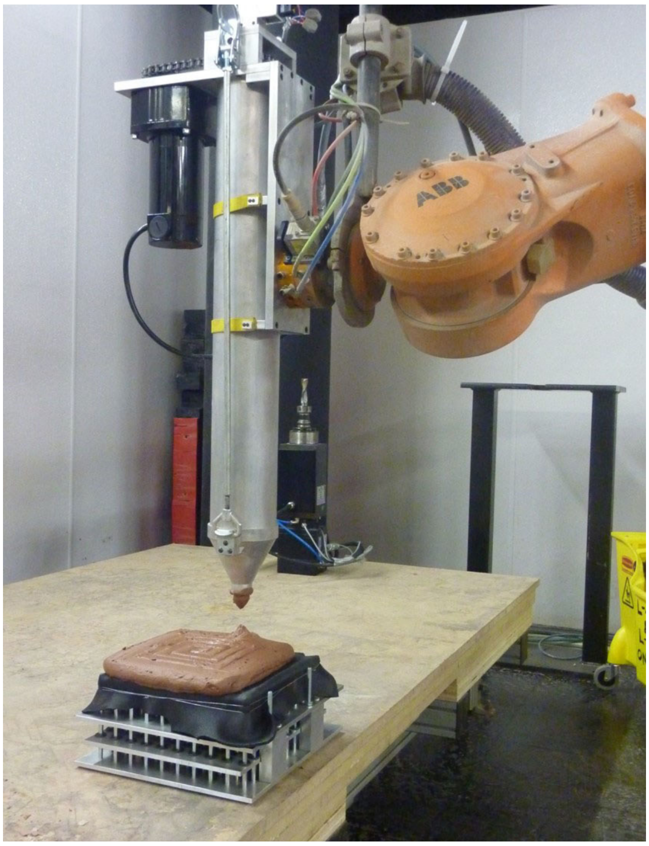

Figure 3. Test print over a pin mold covered with an interpolator membrane.

Industrially made ceramic extrusion systems operate with higher pressures and fairly dry clay bodies, producing relatively stiff parts shortly after the clay exits the extrusion die. Typical hollow extrusions for façades consist of two outer walls of 8-10 mm thickness and a central hollow core of about the same width. Here the adjustable mold could easily be used for slumping elements into three-dimensional shapes. After the extrusion the wet pieces can be shaped on the adaptable mold and remain there until the clay has dried to the green state. The risk of surface dimples from pin indentations in the interpolator sheet are much reduced because the industrially extruded clay is already much stiffer than the clay body used during the experimental robotic extrusion. The reduced water content also reduces the time needed to dry the clay elements to the green state, thus relatively quickly freeing up the mold for the next slumping process.

The adjustable mold combined with the robotic extrusion system can generate complex forms. But limitations exists as to what forms can be built. Overhangs, undercuts and sudden steps in the geometry are difficult to accomplish and require further work as well as the integration of additional support materials.

2.3. Economics of 3D printing versus extrusion

The economics of 3D printing are still a difficult proposition when compared to the efficiency of industrial production methods. This paper uses the case of a complex ceramic piece to determine the approximate production volume where 3D printing is economically feasible. The piece is a module for an exhibition that features a series of walls constructed from a ceramic element that is trimmed at various angles to create

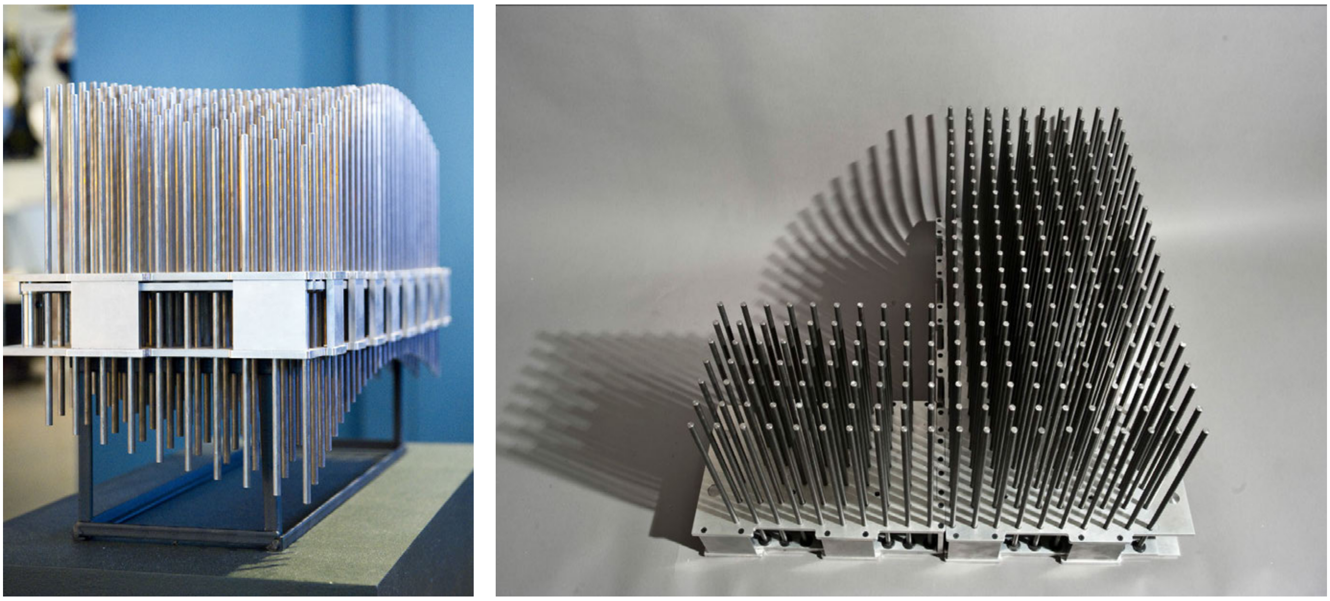

Figure 4. Left: Adjustable pins form complex curved surfaces (Photo: Just Knight). Right: Modular mold elements enable a wide range of element formats with limited mold size.

Figure 5. Clay prototype produced over an actuated pin mold. Surface quality was improved through robotic milling as post-processing operation.

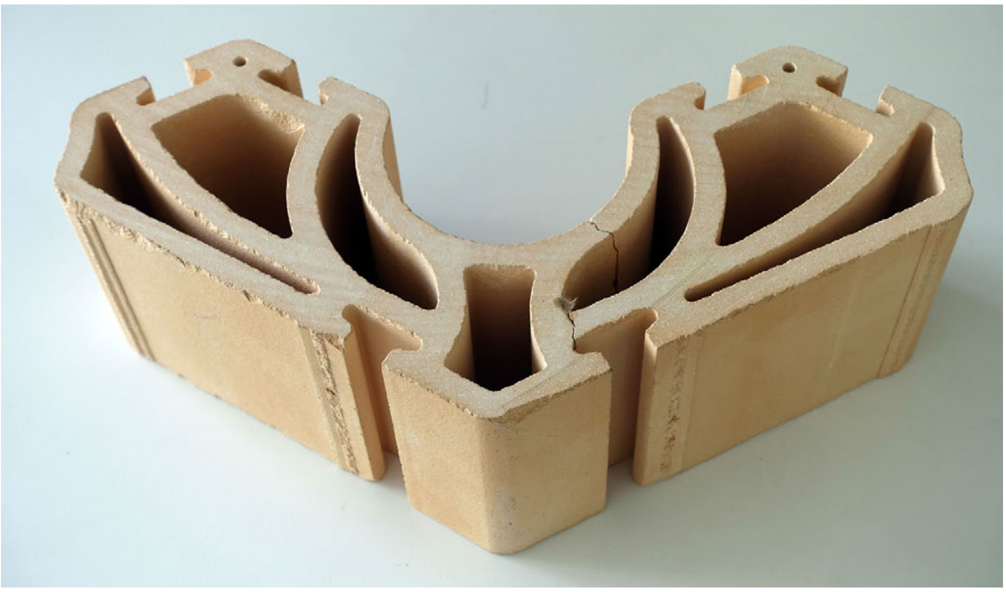

Figure 6. A complex element designed for the extrusion process was used to compare costs with 3D printing. The piece can be arranged into structural wall assemblies. One of the faces is CNC cut at an after firing.

a more complex formal expression (Figure 6). The production run was approximately 800 pieces. The piece itself was designed as an extrusion element for a die that was inscribed in mouthpiece approximately 37 cm in diameter, with a cross sectional area of 161 cm^2. Production costs were estimated by two producers.[2] The cost of the die was identical in both cases, and was assumed as a fixed cost that had to be amortized over the small production run. One producer planned to cut the fired piece on a CNC ceramic saw, which itself involves setup costs and programming time, as well as machine time. Cost estimates from this company per piece took those costs into account. Compared to producing 800 identical pieces the cost penalty of having 50 different cutoff angles was 13 %, the increase in cost for having 100 different cutoff angles was 22 % per piece. These are production costs that do not incorporate the added complexity of handling many different pieces during installation.

The research estimated the cost of 3D printing the pieces instead of extruding and CNC cutting them, using an average depth of 450 mm for the element. Based on a print speed of 15 mm/second, an assumed nozzle diameter of 11 mm and a layer thickness of 10 mm, the print time was approximately 1.3 hours, and the per piece cost around 10 times higher than

[2] The producers asked to remain anonymous.

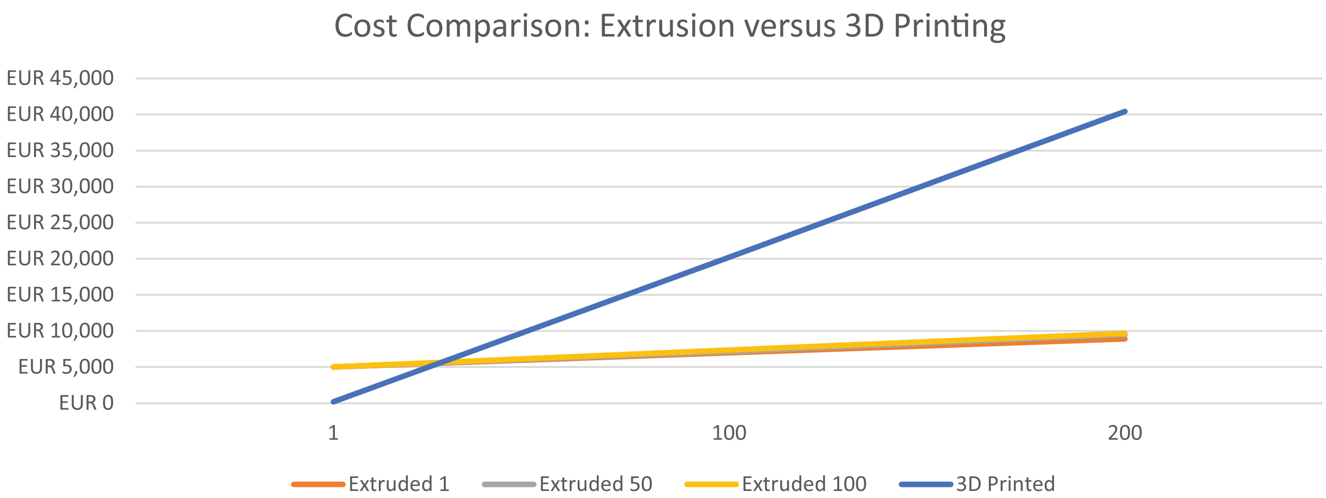

Figure 7. Fixed and variable costs for production of a ceramic module. The near-horizontal line represents extrusion costs for producing elements with 100 different cutoffs. A similar line for 1 or 50 individual cutoffs follows a similar slope.

the cost of the extrusion. In this example a production of approximately 27 pieces would be the breakeven point between 3D printing and extrusion (Figure 7).

This particular piece would not require support by an adjustable mold since the form can be printed vertically, provided that the clay body is dry enough to be self-supporting during the printing and drying phase. An important process aspect is the print resolution and its relationship to the size of the final element.

Is there a future for large ceramic 3D printing? Much will depend on the technical capabilities, print quality, and the associated costs. As the technology matures the cost of 3D printing with other materials has decrease significantly over time – simple machines are now available for low 4 digit US dollar amounts. Assuming that ceramic 3D printing costs follow the same trend it seems likely that the current cost gap between conventional methods and 3D printing will narrow over time. Special pieces are often needed when architects develop custom ceramic elements for façades, and their production now is fairly labor intense and often involves significant fixed tooling costs. 3D printing can be cost effective and save time as well – provided the quality approaches industrial standards. Entirely new expressions are also conceivable based on 3D printing of ceramics, which could also take advantage of expressing the trace of the nozzle during the printing process (Figure 8).

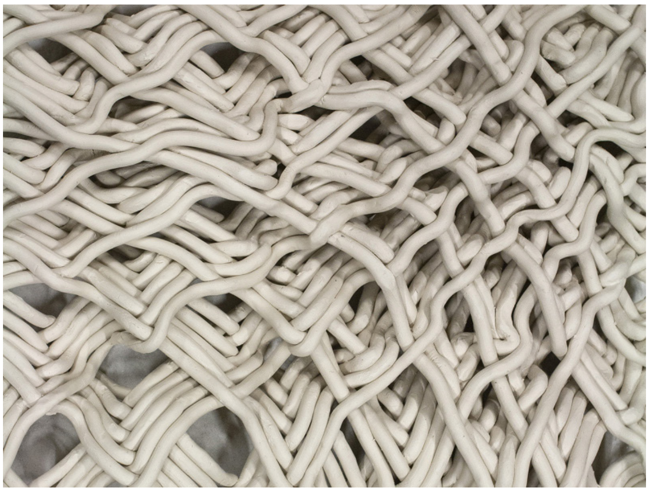

Figure 8. 3D printed ceramic pattern. Study by Jared Friedman, Olga Mesa, and Hea Min Kim at Harvard GSD. Instructors: Nathan King, Rachel Vroman (Photo: Jared Friedman).

3. STRUCTURAL THIN TILES TECTONICS

Much of the innovation focus in the tile industry over the past decade has been the focus on innovative surface textures and glazes. A parallel trend towards larger format tiles has led to recent advances in production technology that allow tile producers to scale up the size of their products, extending capacity to produce extremely large and slender tile elements up to 3.6 m by 1.2 m in size at thicknesses between 3 and 6 mm. These innovative products are used as wall covers, façade claddings, or as furniture finish. Their sheer size, however, suggests that these elements can be considered as sheets that, much like steel or plywood, can be used in any number of applications that utilize its properties and the related fabrication technologies. The MaP+S group has been particularly interested in an investigation of structural opportunities, since the mechanical properties of this material are excellent, production tolerances are low and durability is high. Can we reimagine what a tile can be once it is conceived as a sheet product instead of a surface finish?

To answer this question the research team decided to product design configurations for a self-supporting column within a bounding box of 1.2 × 1.2 m in plan and a height of 3.6 m. At this dimension the capacity of a single sheet is exhausted, and design operations are needed to add stability to configure an overall structural system. The lead designers of the prototypes exhibited at the 2015 CEVISAMA in Valencia, Spain were Mariano Gomez Luque and Pablo Roquero (Figure 9).[3]

[3] Team members included Leire Asensio Villoria (Lecturer Harvard GSD), Mariano Gomez Luque, Felix Raspall, Pablo Roquero, Malika Sing, Zach Seibold, Puja Patel, Amanda Lee, Tiffany Cheng, as well as Felix Amtsberg (TU Graz).

Figure 9. Thin tiles produce tectonic assemblies for the 2015 Cevisama (Photo: ACF Fotografia).

Precedents for structural use of ceramic tiles include the work of R. Guastavino and E. Dieste. Both utilized standard format, small rectangular tiles bonded with mortars. Earlier work by MaP+S in collaboration with Prof. Trummer (TU Graz) resulted in a prototypical shell structure where ultra-high performance fiber concrete is used to structurally bond shaped tiles that were produced in a low-volume setting as slip-castings. The present study investigates possible structural morphologies that enable the new generation of large thin tiles to take on modest structural roles. The design deployed three different operations that transformed the thin and slender tile product into a structural assembly. These operations are cold bending, folding, and cutting.

3.1. Cold Bending

Tiles today are routinely bent after being heated up to soften the ceramic. The new generation of slender and large format tiles, however, have shown the remarkable ability to cold bend in part due to their extreme thinness, in part due to the superior mechanical properties of the materials used. The porcelain clay bodies of these tiles are fired at relatively high temperatures to achieve a vitrified, dense, end product with a water absorption rate of less than 0.4 %. One of the manufacturers calls out a bending strength of 59 N/mm^2 and a breaking strength over a standard testing jig of 458 N (15). Bending tests conducted by Felix Amtsberg, visiting scholar from the TU Graz at the MaP+S group for this project, in-

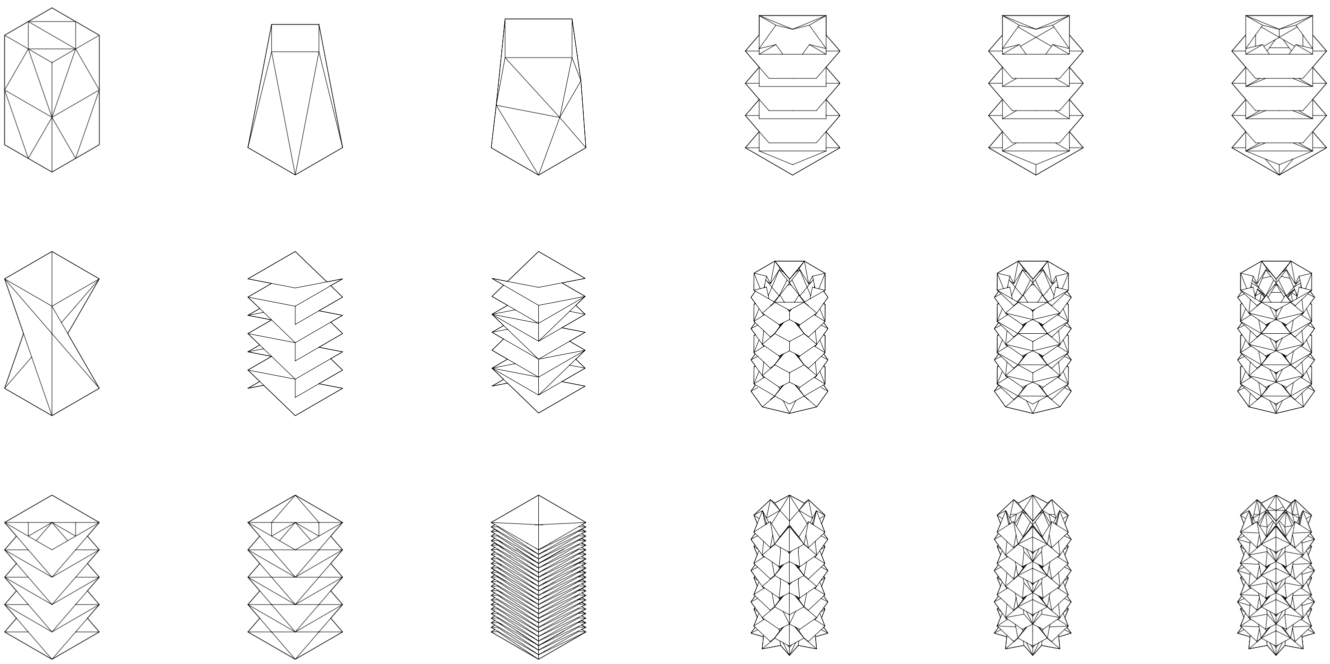

Figure 10. Self-supportive assemblies that derive strength and stability through cold-bending the ceramic tile.

vestigated cold bending of 3 mm porcelain tiles reinforced with a glass-fiber backing mesh. The tiles were cut to specimen measuring 80 mm in width and were bent over a curved mold, with the glass-fiber backing on the compression side of the element, thus without any impact on the stress distribution in the cross section. 3-point bending tests with calculations of maximum bending stresses and Young's modules were also conducted. The experiments suggested a minimum bending radii of 3 m under lab conditions. Associated maximum strains are $\varepsilon = 0.005$ %, based on $\varepsilon = y/R$. Here y is half the thickness of the tile, and R is the bending radius. Other tests showed that tiles from a different production batch with different colors may fail earlier – a reminder that designers are well advised to test the actual material batch in order to prevent unexpected failures during cold-bending.

Based on the test results a series of design studies were conducted, whereby cold bending was used to stabilize the slender elements and prevent out of plane buckling in compression or bending. The bending stresses induced through cold bending at the small radii mentioned above are near the limit of what the tiles can support. Any additional tensile or bending stresses thus have to be perpendicular to the curvature of the tile, thus be aligned with the straight ruling lines. The Harvard team explored several options. Two options were chosen for further development, and prototypes were produced both in-house as well as by a partner company in Spain. Based on prototyping the stacked version was ultimately built (Figure 11).

The cold-bent model involved stacking 7 volumes, each of which had been pre-assembled from cold-bent 3 mm ceramic tiles at a bending radius of 6 m. The tile contours were CNC waterjet cut to match the final shape in their bent condition. During the assembly of the 'boxes' the tiles were clamped against a steel female mold and connected with a fiberglass/resin fillet joint along the edges. A diagonal system of wood struts was used to maintain the desired curvature after the assembly was removed from the mold. Shear connections between the stacked units were provided by connecting the interior wood structure vertically (Figure 15).

3.2. Folding

Folding as an operation to create structurally capable ceramic prototypes does not necessarily involve bending, but can maintain the flatness of the base element. Buckling and other stability issues here are addressed through the configuration of systems whereby each tile receives edge support by means of its connection to the adjacent tile. The folded edge effectively acts as a beam. Folding is a well familiar strategy used in folded plate structures on a larger architectural scale (16), it is also familiar from smaller explorations of origami (17), (18). Folding has not been looked at as a strategy for generating tectonic tile assemblies.

Thin tiles are routinely produced with a glass-fiber mesh adhered to the back side, a strategy that reduces cracking of tiles during transport and installation. Cutting the tile but not the mesh produces a live hinge that can serve as a structurally effective, yet simple to produce strategy to develop spatial arrangements from 2-D flat tiles. The research team conducted a series of test cuts on a multi-axis robotic waterjet, developing the cutting parameters such as speed and cutting abrasive that allowed for cuts exclusively through the tile, leaving the mesh intact.

Based on the success of these experiment a series of design studies then explored different folded morphologies, again geared towards producing a stable column 3.6 m tall over a 1.2 × 1.2 m base. The number of flat tile segments needed to produce each structure varies between 9 and 464 – a number that indicates the resolution of the folded elements relative to the overall size. Some designs included large face tiles connected at moderate angles to adjacent elements, others produced strongly spatial tessellations or even represented a modular approach with folded 'building blocks' used to construct a column (Figure 10).

The design chosen as a prototype utilized the maximum number of pieces, but the repeated use of two different modules facilitated the pre-fabrication as well as the assembly. The waterjet used in production could not be adjusted to only cut through the tile and maintain the integrity of the mesh. Production ultimately generated a large number of ceramic pieces that were assembled in two female molds (Figure 12). The all-important edge connection was easily accomplished with hot melt adhesives and polyurethane construction spray foam. The resulting modules were extremely precise and formed the overall columns without any need for tolerance adjustments. Due to the stability of the base material the modules could be easily stacked and bolting together into a structurally viable assembly.

Figure 11. Pre-installed element with bent tiles as the outer surfaces (Photo: Jordi Font de Mora, Grupo on Market).

Figure 12. Female molds were used to assembly precise modules that, once stacked and bolted together, formed a structurally active prototype (Photo: Jordi Font de Mora, Grupo on Market).

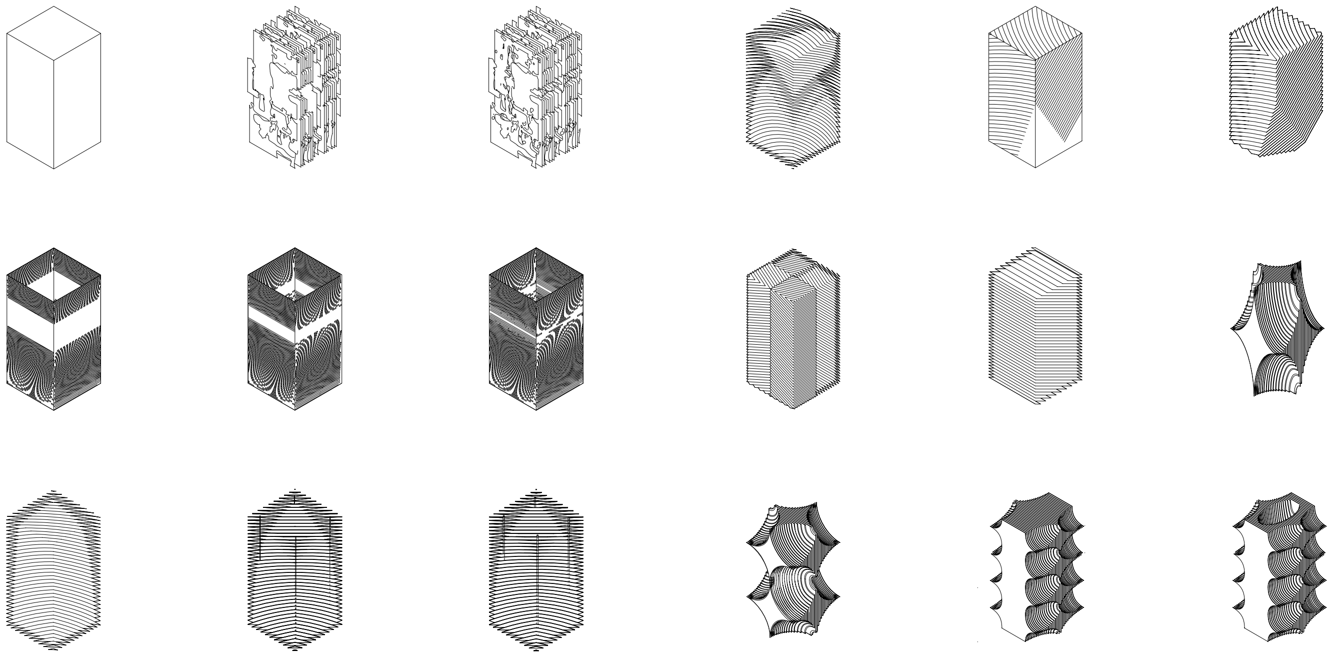

Figure 13. Cutting and the aggregation of tile sheets in parallel layers can produce intriguing visual effects.

3.3. Cutting

The third series of operations on the thin ceramic sheets was based on CNC waterjet cutting, which allows complete geometric control and permits intricate as well as otherwise challenging patterns and forms to be created consistently (Figure 13). While not inherently an operation that creates stability and strength from the thin tile sheet, cutting in combination with an aggregation of multiple tiles will produce tectonically viable results. CNC cutting can produce a wide range of effects from flat tiles and their Moiré-like perforations to stacking effects where dimensional variation creates a variety of opacities and translucencies. The strategy ultimately chosen for the exhibition piece focused on a spatial description of larger voids through the contour-cutting of the tile, thereby exposing the edge as a primary reading of form making.

The thin tiles can be easily connected with threaded rods and systems of spacers and nuts. At each connection a moment joint is produced by post-tensioning the inner threaded rod such that a pipe-shaped spacer tightly clamps the tile (Figure 14). The stiffness produced by multiple connections adds up to an overall system stiffness that suffices for the creation of a column of the desired proportion. By eliminating structural elements other than the tile the visual focus shifts from the tile surface to its exposed edge, subverting the typical conception of tile as a surface cover.

The tile contours for the prototype were cut on a 2.5-axis CNC waterjet. Due to limited available bed sizes two horizontal joints were introduced, dividing the overall column into three segments. Each segment is connected with four threaded rods as described earlier. Vertical metal profiles in the interstitial space between 4 adjacent tiles ensure alignment such that the tiles can bear vertically on each other. Lateral stiffness is provided by the in-plane stiffness of the tiles in one direction, and by the aggregate stiffness of the moment connections between threaded rods and tiles.

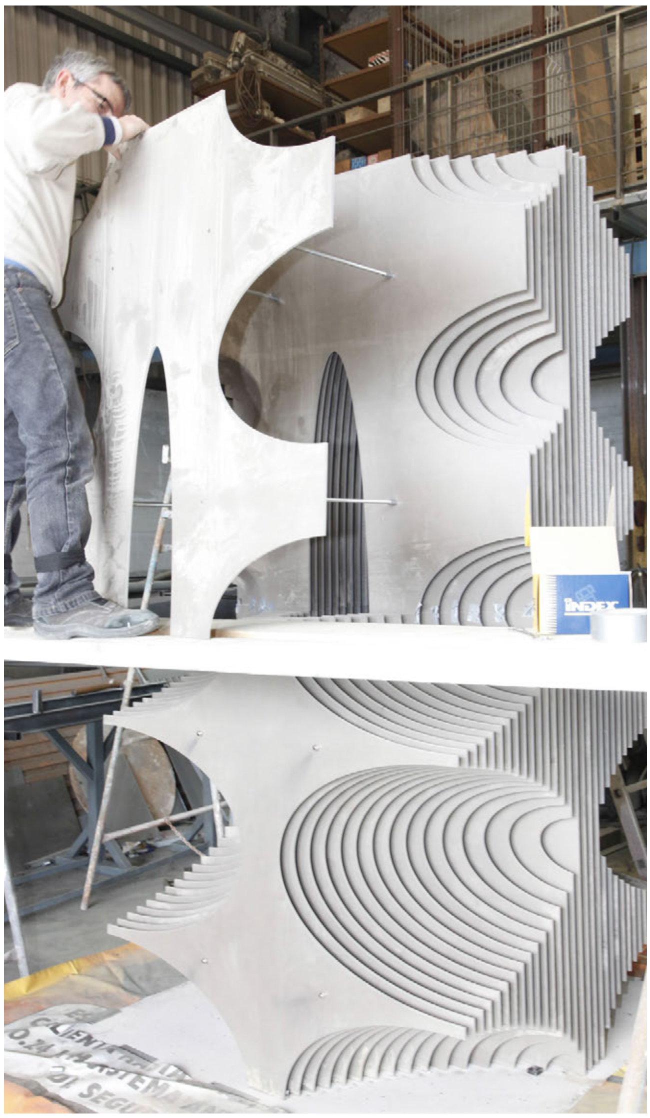

Figure 14. Assembly and post-tensioning of tile sheets (Photo: Jordi Font de Mora, Grupo on Market).

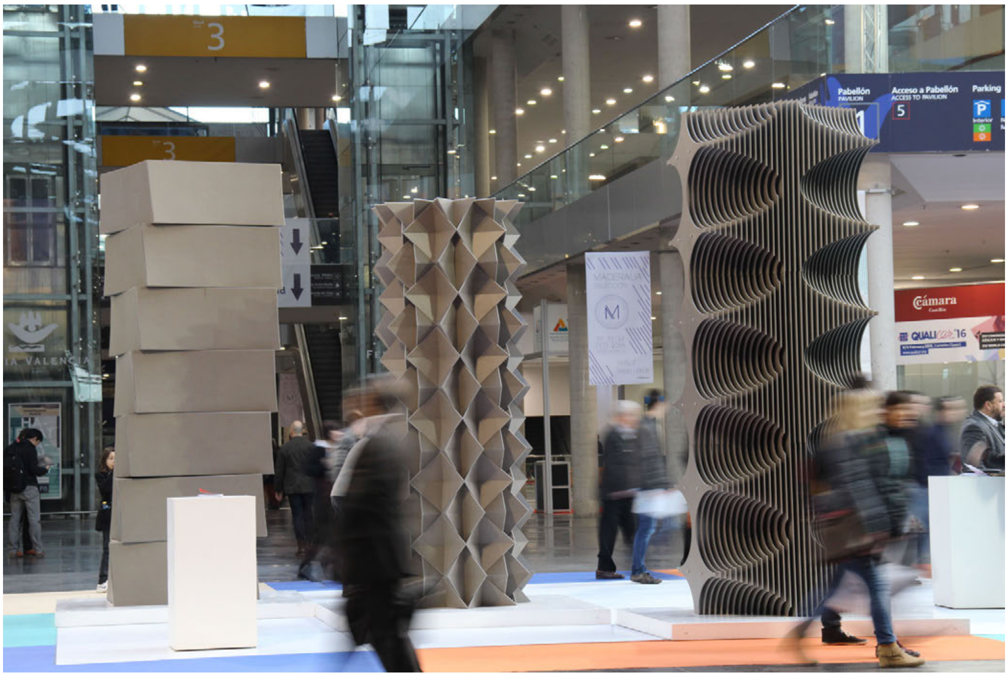

Figure 15. The final setup in the main access lobby of the fair grounds.

All three columns were pre-assembled in the shop and transported by truck to the fairgrounds in Valencia. The overall exhibition showed additional research and smaller 3D printed scale models of many earlier design studies (Figure 15).

4. CONCLUSION

Innovation in the ceramics industry is expanding beyond novel glazes and tile formats. 3D printing, while still at the development stage for larger elements, shows promise as a strategy for special pieces in the near future, and in the long term for highly varied modular designs that cannot be produced with traditional manufacturing techniques. More research is needed to improve surface quality and reduce the porosity of the fired clay body in order to allow for applications both on the interior as well as on the exterior. As demand grows costs will decrease, opening up incrementally larger markets. 3D printing might also blur the boundaries between artistic and industrial modes of making, for the mutual benefit of both domains.

Technology development, however, is risky and relatively slow. Rethinking what a tile is can open up new design opportunities immediately, especially when utilizing existing industrially produced elements. Large tile formats have been underutilized as surface finish. When designed with structural needs in mind these elements can produce intricate as well as functional tectonic prototypes. More challenging than the limitations of the material system is actually the lack of companies experienced in handling these new kinds of assemblages that require more extensive fabrication experience far beyond what tile installers are trained to do.

The design studies presented for the exhibition design show fundamental principles – it is up to design teams to adopt these and develop related morphologies and find applications for interiors as well as for exteriors. Façades and other secondary structural elements could easily be configured based on the principles presented here, combining flat-to form principles with the compelling longevity and precision of ceramic sheets. As we rethink ceramic tiles as *ceramic material systems* existing mental barriers for design recede, and give way to a new approach that takes the material for what it is – a contemporary way to materialize the imagination.

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