Flowing matter: Robotic fabrication of complex ceramic systems

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Purpose This research investigates the possibility of adapting industrial fabrication methods to produce mass customized ceramic components for complex tectonic systems. The aim is to bring the practice of building ceramic structures close to the contemporary production context by proposing a revision of a well-established production method – clay extrusion – and informing it with deep computational design and robotic fabrication techniques. **Method** The envisioned industrial scenario is emulated by fabricating a series of ceramic prototypes through the use of a 6-axis robotic arm equipped with a wire-cutting tool, developing ruled-shaped interlocking clay units for the creation of innovative load-bearing walls. A systematic workflow allows for the direct stream of information from a parametrically-discretized input surface to the generation of cutting paths for shaping clay bodies through the robot. **Results & Discussion** The combination of high-tech computational design and robotic fabrication processes with low-tech onsite assembly allows for the generation of serialized mass-customized ruled-geometry ceramic units for hybrid structures, such as doubly-curved loading-bearing walls with enhanced structural performances. The result is a fast, economic, and efficient way to fabricate highly differentiated ceramic components with the use of robotic technologies.

***Keywords**: robotics, industrial automation, ceramic structures, computational design*

INTRODUCTION

Ceramic materials have a long history as a building material in architecture, and are used in structural, cladding, and decorative applications. Today's dominance of flat rectangular tiles – a ubiquitous ceramic building component – is now challenged by newly emerging numerically controlled methods of ceramic production and assembly. Both craft-based tile manufacturing and high-volume industrial production of clay-based ceramics are affected by digital and robotic fabrication techniques but the potential for these new tools to enable new ceramic products remains in their infancy. Of particular interest for architects is the plasticity of clay based ceramics prior to the kiln firing – a property that potentially allows for the realization of novel complex forms. Rather than merely designing a novel ceramic part, this paper presents an approach that addresses the material and its associated processes as an integral and inseparable unit. Only the synergetic consideration of both – paired with novel prototyping approaches using an industrial robot – leads to the proposal of an innovative building component that can be feasibly produced in the context of the contemporary production of architectural ceramic. This approach was the subject of the course "Material Processes and Systems: CeramicLab" taught by Prof. M. Bechthold and Nathan King in the fall of 2011 at the Graduate School of Design at Harvard University.

The project presented here takes a particular interest in the design and construction of complex tectonic shapes. The resulting forms combine traditional as well as new methods of surface discretization. The basic building component is a newly designed interlocking block which has been conceived of as a mass-customized element. Following an analysis of typical industrial production processes for ceramic architectural elements, the team decided to develop a new variable structural ceramic block based on a novel variation of the widely used extrusion process.

The project addresses the long-standing problems inherent in the construction of complex form using traditional brick-laying techniques and standard bricks. In order to create non-orthogonal, complex overall forms mortar joints that are normally approximately 1 cm in thickness have to vary in size, resulting in highly differentiated mortar patterns on the finished surface. Complicated and expensive scaffolding systems for both guiding and supporting the ceramic units are normally required during the construction of such complexly shaped structures. As skilled craftspeople are no longer widely available, and considering high labor costs in the construction industries of industrial economies the realization of complexly shaped ceramic surface forms has become highly problematic.

Addressing these problems, the research explores the opportunities specifically associated with the merger of *high-tech* industrial production processes of customized components with *low-tech* on-site assembly. A novel variable extrusion process was developed and prototyped using a robotic work cell. The resulting twisted and curved block elements are evaluated in the context of several design prototypes that derive novel design expressions through the availability of mass customized ceramic components.

The research proposes to enhance standard industrial extrusion processes with a variable wire cutting module that allows the production of components with a wide variety of curved but ruled surface geometry. The industrial production context was emulated through the deployment of a prototypical robotic wire cutting process driven by an integrated digital workflow. Precisely interlocking units were designed and produced using the system. In the construction context these newly shaped ceramic blocks might eventually reduce or even eliminate the need for temporary guiding systems and reduce the use of temporary supporting structures. In addition, a ruled discretization method would allow for a smoother definition of complex spatial surfaces. Finally, the resulting geometry of the overall interlocking system may introduce enhanced structural stability especially when combined with post-tensioning methods.

This paper first reviews construction precedents – both and historical and contemporary – of complexly shaped tectonic ceramic forms. It then describes the established industrial production of ceramic components with a focus on identifying opportunities for implementing robotic technologies for producing computationally designed ceramic units. The envisioned industrial environment is finally simulated through the use of robotic wire-cutting techniques for the fabrication of a series of prototypes that serve as a proof of concept.

BACKGROUND AND PRECEDENTS

The traditional stone construction techniques of pre-medieval periods are among the first precedents of complex block surfaces. Stone elements were often customized according to their location or structural role, but preference given to the use of similarly shaped elements that culminated in the central keystone. This logic has continued in the construction of later vaults and domes, generating more spatially complex masonry structural systems. Gothic architecture employed more advanced versions of earlier stone and brick vaulting techniques in the pursuit of seemingly lighter, intricate structural patterns. Of particular significance in more recent periods are the works of Eladio Dieste and Rafael Guastavino. Both devised novel construction systems of structural ceramic surfaces using standard format tiles. Dieste's structures require an extensive scaffolding system – but he was able to achieve relatively complex forms[2]. Guastavino, on the other hand, remained largely constrained to relatively simple dome and vault shapes – his innovation was focused on the much reduced need for temporary scaffolding systems and improved fire resistance of horizontal spanning systems[3]. Another relevant historical precedent is Antonio Gaudi's Sagrada Familia, whose ruled-geometry building components required the expertise of highly skilled craftsmanship[4].

Fig.1. Construction of a ceramic surface by Eladio Dieste using extensive scaffolding, (Image courtesy of Prof. Martin Bechthold)

In traditional dome construction, brick and stone layers are horizontal rings. Typical Arctic Igloo construction employs ice blocks manually shaped on site, and assembled following a spiral pattern such that the blocks form an interlocking structure. A more recent example of curved brick surfaces is David Wendland's Experimental Construction[5] – a research project culminating in the erection of a free-form shell masonry structure that required the employment of an intricate doubly-curved scaffolding system for holding and guiding the assembly.[5] The free-form Catalan thin vault by Philip Block's BLOCK research group also served as an important precedent, particularly for its non-standard discretization of masonry structures[6]. Relevant to the research is also the work of Martin Speth, who has developed doubly-curved masonry vaults made of prefabricated components[7]. These examples all deal with complex shape, rely on an external means of prescribing overall geometry on site, and accommodate surface curvature through variation in the thickness of mortar joints- none deploy a custom shaped block element.

Several emerging technologies are available to assist with the assembly of complex structures on site. GPS-assisted construction approaches are being actively developed, and barcode systems are used to manage large sets of individualized components on contemporary construction sites. Both technologies are potentially relevant within the context of the research presented as they can guide the assembly of numerous highly differentiated building components. One of the few broadly implemented mass-customization systems in brick and block construction is the German Xella system by Xella Kalksandstein GmbH's production logic. Here, sets of blocks that combine custom and standard formats are configured and delivered on site using just in time strategies thus eliminating the time-consuming and wasteful cutting of blocks on site, and facilitating the decrease in construction time through the deployment of small cranes operated remotely by masons[8]. While this system does employ custom pre-cut units it is currently only used in the construction of flat walls.

PRINCIPLES, PROCESSES, AND OUTCOMES

This design proposal is conceived as a design research investigation whose objective is to develop a prototypical manufacturing scenario that can be used to evaluate design assumptions, material properties, fabrication constraints, and assembly logics of the proposed process intervention. The research is carried out under the hypothesis that the use of custom shaped ceramic components incorporating off-site robotic wire-cut ruled geometry embeds global geometric intelligence and allows for low-tech on-site assembly while achieving complex doubly-curved continuous-surface ceramic structures with interlocking components. This research project links the established industrial production of ceramics with the intelligence of computational design and digital fabrication by intervening in a standardized production process –extrusion – through a novel use of robotic technologies.

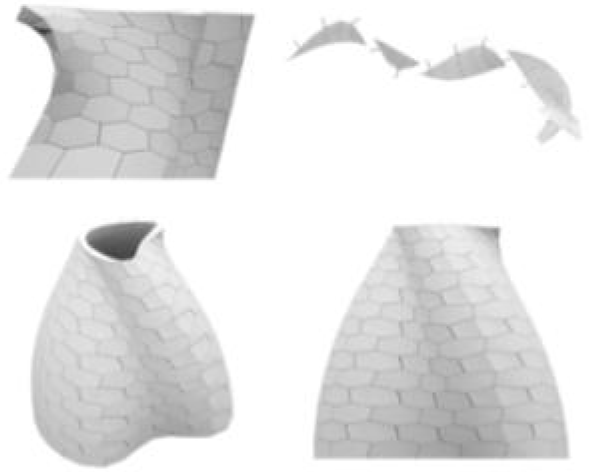

Fig.2. Examples of potential complex tectonic systems

INDUSTRIAL CLAY EXTRUSION

Fig.3. Industrial processes of clay extrusion (Image courtesy of the Design Robotics Group, Harvard GSD)

Industrial clay extrusion is a process in which ceramic components are produced in a serialized and continuous linear manner. During the process a helical extrusion mechanism forces clay through a die that imposes a continuous shape on the material. The extrusion die represents one of the only integrated mechanisms for custom shaping in industrial ceramic production. Custom extruded sections come a cost premium associated with die development that must be justified by a significant production quantity allowing for the production of many of the same custom components rather than individually differentiated parts. During extrusion, components are supported by a conveyor or roller system that carries the extruded elements through several automated production cells that dimension, fire, finish, and package the ceramic parts.

Fig.4. Industrial processes of cutting clay elements (Image courtesy of Design Robotics Group, Harvard GSD)

Dimensioning of individual linear elements is often accomplished by automated and exactly coordinated wires or blades that make cuts perpendicular to the extrusion direction. The proposed process intervention adapts the integrated dimensioning cell to incorporate a numerically-controlled wire-cutting tool designed to enable shape customization of single elements during linear processing. In this scenario robotically-guided wires are programmed to cut each component along ruled surfaces. Part dimensioning during industrial extrusion is characterized by wire-cutting that, when numerically controlled, could achieve complex ruled surfaces on all non-supporting block faces. By addressing customization through the intervention in a single production cell within the larger extrusion system the proposed process would enable the manufacturing of mass-customized ceramic elements defined by ruled geometries.

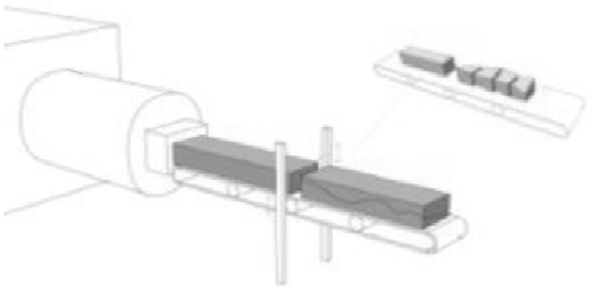

Fig.5. Envisioned industrial custom-shape cutting

RULES SHAPED CUSTOM COMPONENTS FOR COMPLEX TECTONIC SYSTEMS

The proposed combines the CNC wire-cutting of ruled-geometry with and intelligent computational design approach for use in the design and construction of complex ceramic structures. A rigorous computational method was developed to optimize a surface discretization with customized units that embed the following characteristics:

- The traditional masonry logic including an arrangement of staggered components for optimal structural performances.
- A precise interlocking system, in which each component aligns with the ones around it.
- A smooth subdivision of the surface, with linear-seams representing edge lines of singular ruled surfaces.
- A potentially enhanced static behavior, with an increased shear resistance of the overall structure over traditional brick walls.

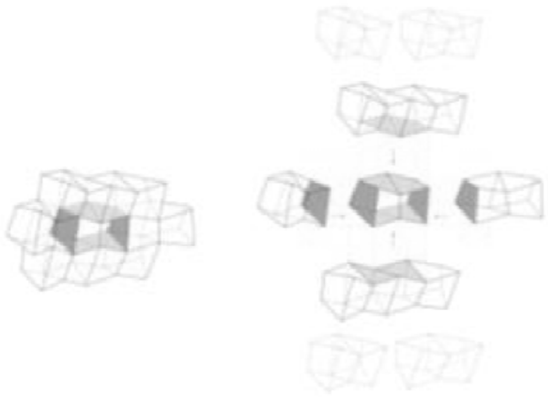

Fig.6. Interlocking logic embedding geometric assembly intelligence

The developed algorithm, implemented in a C# component for *Grasshopper*^{TM}, the graphical algorithm editor for the design software *Rhinoceros*^{TM}, allows for a straightforward discretization of input surfaces with a series of parameters that allow a flexible customization of the system's geometric properties. The algorithm constitutes the first step in a linear workflow from the digital conception of the tectonic system to its components' fabrication and the final structure's assembly. Following this logic, the developed computational method allows the extrapolation of geometric information needed for an automated fabrication process. For each ceramic component the algorithm outputs wireframe data that serves as guiding lines for the ruled-geometry wire-cutting method.

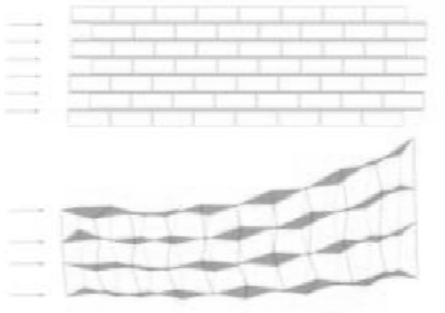

Fig.7. Enhanced shear resistance through volumetric seams

PROTOTYPICAL OFF-SITE ROBOTIC FABRICATION

Consistent with most commercial masonry construction systems the proposed system utilizes off-site production of individual units. To facilitate the exploration of of-site mass customization established by the proposed production system an automated robotic programming workflow was used to derive machine code from the previously described digital geometry within the same *Rhinoceros*^{TM}-based digital design platform.

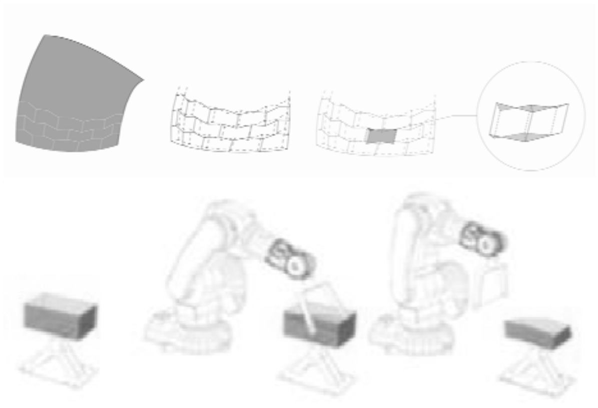

Fig.8. Process workflow: from surface discretization to robotic wire-cutting

Industrial numerically controlled wire-cutting was simulated during prototyping by a 6-axis industrial robotic manipulator that was used to guide a custom end effector that employed a steel cutting wire. For each individual component the workflow began by processing the input data derived from the digital model. First, the wireframe geometries describing the unit's edges are used to define ruling lines and generate the wire-cutting information for the robot. Once positioned relative to the robotic work cell these lines served in the generation of cutting paths along five sides of each element.

In contrast to previously published work[1], automation of robotic programming was facilitated by the *Hal*™ plugin for *Grasshopper*™ which was used to generate, simulate, and optimize each of the paths. To further verify the cutting path, each robotic movement was simulated in proprietary ABB simulation environment *RobotStudio*™.

A custom fixture was created to support the wet clay block during cutting. To facilitate maximum robotic freedom the fixture supported the clay well above the work surface using a stanchion that engaged the material platform inboard of the stock perimeter allowing the tool to realize the undercut geometry needed for the interlocking units. Finally, a numeric labeling was used to identify each unit during assembly.

Multiple prototypes were created to better understand the application of different ceramic compositions (terracotta, porcelain, T1, and brown stoneware). An analysis of the prototypes revealed that the accuracy of the cutting process is the result of the combination of several aspects: moisture and grog content within the clay, adhesion level (meaning how difficult the cut part is to remove from the stock), wire tension and cutting speed. Further testing revealed that a clay of relatively high grog content, with high green strength, that is designed for low shrinkage gave the best finished results of all tested bodies. Additionally, if the drying and kiln schedule is regulated, shrinkage can be predicted within acceptable tolerances in the geometries tested (Figure 10). Further investigation is required to determine the full impact of material shrinkage which, as seen in figure 13, can have an aggregate impact on the overall surface geometry.

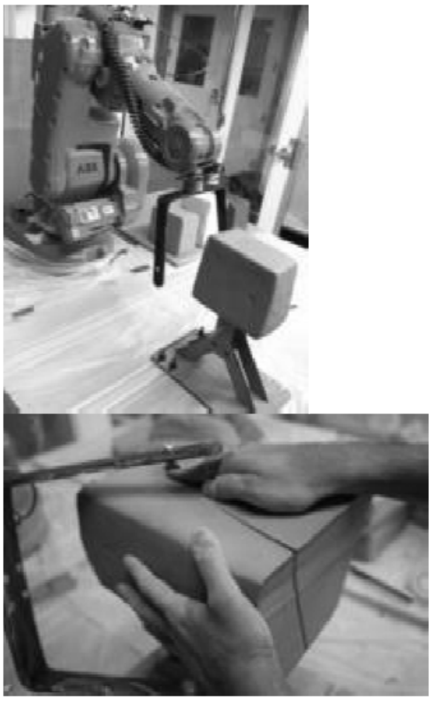

Fig.9. Robotic fabrication of ruled-geometry ceramic components through a wire-cutting tool

Fig.10. Fired ceramic elements were tested for shrinkage and interlocking capacity.

PROTOTYPICAL ON-SITE ASSEMBLY

The described ceramic components are characterized by an inherent geometric logic that can be used to indicate assembly sequence. This logic, when combined with an assembly drawing and factory applied numeric coding system, allows for intuitive onsite assembly, a limitation of many mass-customization proposals.

Fig.11. Wire-cut ruled-geometry ceramic component

Two full-scale sectional prototypes were developed to test the potential of structural assemblies. The first structure (Prototype A) is an experimental application of the overall process of interlocking discretization of a complex surface. The second (Prototype B) investigates a more speculative use of the ruled-geometry logic for design compositions.

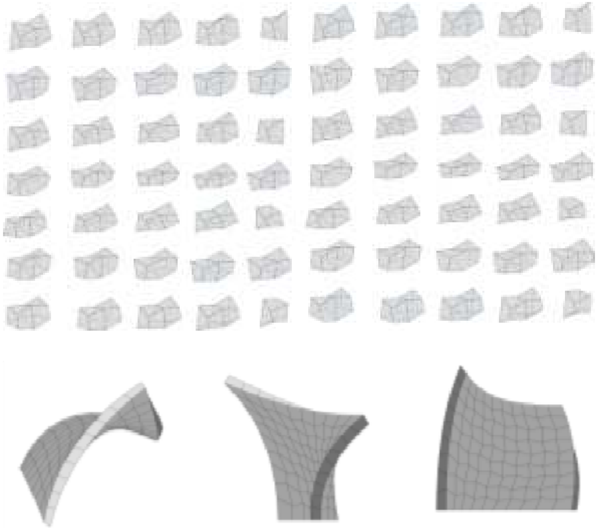

Fig.12. Prototype A: geometric configuration and individual bricks.

Prototype A is formed by interlocking custom components made out of a T1 stoneware with a fine grog content. This prototype tests the ability of the system to create doubly curved surfaces and the on-site assembly logic. While the assembly sequence was consistent with expectations the aggregate shrinkage impacted the ability of the structure to self support during assembly. Additional testing is in progress to resolve these tolerance issues through manipulation of the computational geometry, controlled drying and firing, and clay body specifications.

Fig.13. Prototype A: unfired elements and wall assembly

Prototype B consists of brown stoneware elements designed to introduce a combination of aesthetic and performance opportunities made possible by differentiated cuts for creating non-uniform patterns and apertures.

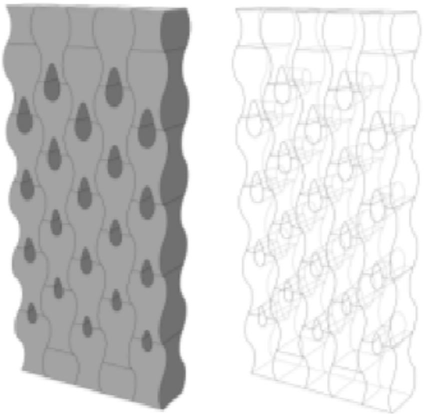

Fig.14. Prototype B: geometric configuration

CONCLUSION AND OUTLOOK

The presented research proposed an industrially integrated process allowing for the manufacture of mass-customized structural ceramic elements through the introduction numerically controlled cutting to the clay extrusion process. The combination of high-tech computational design and robotic fabrication processes with low-tech on-site assembly resulted in the generation of highly differentiated ruled-geometry ceramic units for complex tectonic assemblies.

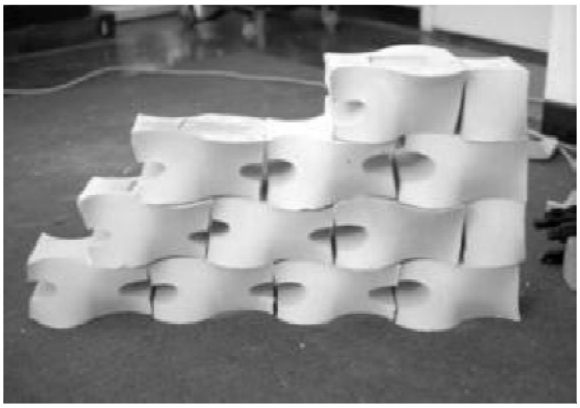

Fig.15. Prototype B: unfired ceramic elements and partial assembly simulation

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