shortages anywhere. A direction for development of a comprehensive mesh detailing and modeling approach would be continued use of a digital-physical feedback loop process in order to introduce darting of the mesh at select locations.

If computational resources allowed for digital modeling of the project's half million rings and all of their physical characteristics and relationships, there would be no need for a digital-physical feedback loop process. In this case, the physical environment would yield no more information than would the digital. The challenge is in developing digital models that possess appropriate abstractions of physical behavior while allowing for efficient modeling and computation using available resources. A digital-physical feedback loop allows for testing of abstractions to see which ones can be made without jeopardizing the integrity of the digital simulation. In the case of the Kukje Art Center, the authors began with a highly abstracted digital representation and gradually rejected counterproductive abstractions, such as the averaging described in Section 3.2. Beyond chain mail mesh, other material systems can benefit from a digital-physical feedback loop process, particularly systems with dynamic behavior or systems with many interrelated parts that defy direct digital modeling and instead require substantial abstraction. When it is unclear what abstractions will be productive, a digital-physical feedback loop process is an effective means for structuring exploration.

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WORK IN PROGRESS

TECTONIC TESSELLATIONS:
A DIGITAL APPROACH TO CERAMIC STRUCTURAL SURFACES

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ABSTRACT

Structural surfaces represent a realm that interweaves formal explorations, structural optimization, and innovation in construction. Computation radically advanced the design of structural surfaces; however, how to translate these structural forms into architectural assemblies at the scale of buildings constitutes the most persistent challenge. In this scenario, an approach that ties advanced digital design tools to a specific ad hoc fabrication method can produce a feasible design and construction system, which can contribute to understanding and overcoming some of the current limitations of structural surfaces.

This research develops an integrated digital workflow that combines form finding with robotic fabrication, surface tessellation, and panelization. In the past years, the use of digital tools to assemble identical modules into complex formations has achieved significant results for loadbearing walls. Expanding this line of research, the proposed fabrication system carries these experiments in additive fabrication into the production of structural surfaces. The assembly sequence involves two-step fabrication: off-site panel manufacturing and on-site assembly. The main components of the system consist of two triangular ceramic pieces that provide structural resistance, refined surface finish, and formwork for the thin reinforced-concrete layer. Panelization strategies reduce the requirements for on-site work and formwork.

The paper describes background research, concept, the form-finding and construction process, methodology, results, and conclusions.

figure 1
Rafael Guastavino. Interior finishing.

figure 2
Eladio Dieste. Complex reusable formworks.

figure 1

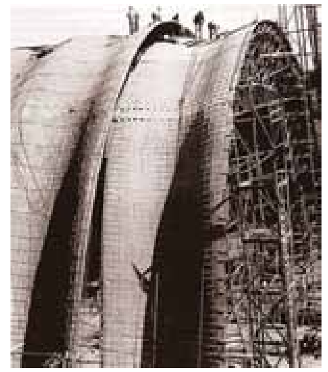


figure 2

1 INTRODUCTION

Structural surfaces have always been admired due to their lightness, elegance, and material efficiency. For certain scenarios, structural surfaces built with ceramic components have proved more suitable than concrete shells, taking advantage of the lower weight and cost of ceramics elements, the subsequent reduced need for reinforcement, and the unique quality of its finishing (Figure 1).

After a period of development, with milestones in the work of Guastavino and Dieste (Figure 1), ceramic structural surfaces became unaffordable, and their use is today almost nonexistent (Collins 1968; Ochsendorf and Freeman 2010). The main reasons for their falling out of favor include the need for expensive formworks in the case of Dieste (Figure 2), and intensive and skilled hand labor in both Dieste and Guastavino (Anderson 2004). In addition, architectural language moved to rationalistic and straight lines. Today, as formal sensitivity reappraises complex curved geometries, digital tools for design and fabrication are capable of reducing the technical limitations and making structural surfaces feasible again (Bechthold 2008). Applications of digital tools for structural assessment proved useful in the rediscovery of tile vaulting by Ochsendorf and Block, and in the development of form-finding tools and fabrication experiments with masonry at ETH (Ramage et al. 2010). However, these studies cover compression-only surfaces and rely on intensive hand labor.

2 TESSELLATED CERAMIC STRUCTURAL SURFACES

The research proposes a new construction process for ceramic shells that reduces the requirements for complex formworks and on-site fabrication, while taking advantage of the lightness and unique interior finishing of ceramics. It differs from previous methods by digital manufacturing tools and panelization strategies. Fabrication of reinforced ceramic panels in a controlled environment using precise CNC equipment reduces the requirements for on-site work and skilled hand labor. On-site assembly is therefore significantly simplified, lowering the number of elements involved in the process from thousands to dozens, and minimizing the complexity of scaffolding. The following sections of this paper will present in more detail the proposed design and fabrication sequence, research methodology, prototypes, results, and conclusions.

3 SURFACE DEFINITION, TESSELLATION, AND PANELIZATION

3.1 Definition and Tessellation of the Structural Surface

The design and fabrication sequence starts with the definition of a base surface and the study of its structural performance. Given the ambition of the project to develop a complete workflow from design to fabrication within a limited timeframe, the project started by looking at compression-only

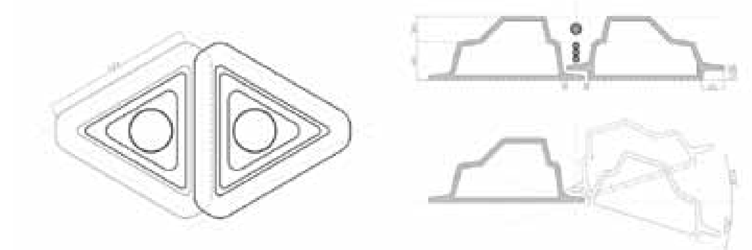


figure 3

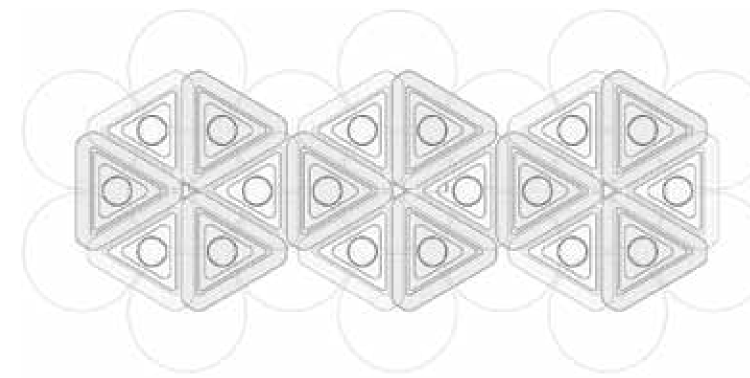


figure 4

figure 5a

figure 5b

figure 3
Geometry of main ceramic components.

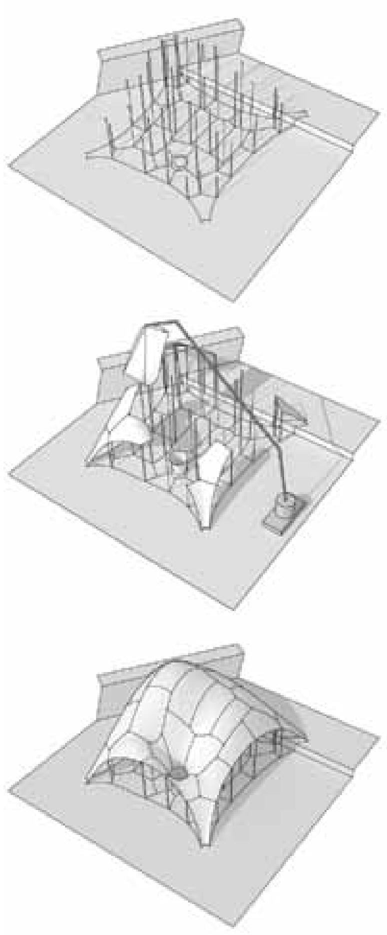
figure 4
Typical arrangement of ceramic elements and detailed section.

figure 5a
Compressed sand milling.

figure 5b
Pin system test.

surfaces, in which form finding has been more widely tested. For this purpose, a particle-spring system component was programmed in C# to estimate compression-only forms: a digital version of hanging models (Killian 2005). In the future, the project will include more complex thin-shell structural forms, which can also be materialized with the proposed fabrication method.

The resulting surface, subdivided into a triangular pattern, accommodates the main ceramic components of the system: two interlocking triangular pieces (Figure 3), designed to create a continuous ceramic surface on one side and to provide space for steel reinforcement and concrete mortar on the other. The interlocking detail of the two pieces accepts a rotation of +/- 17°, and its grouping allows for surfaces with different types of curvature from flat to anticlastic. The tessellation process mediates between the geometry of the piece—which favors an equilateral pattern—and the deviation from the optimal structural surface.



figures 6a, 6b and 6c

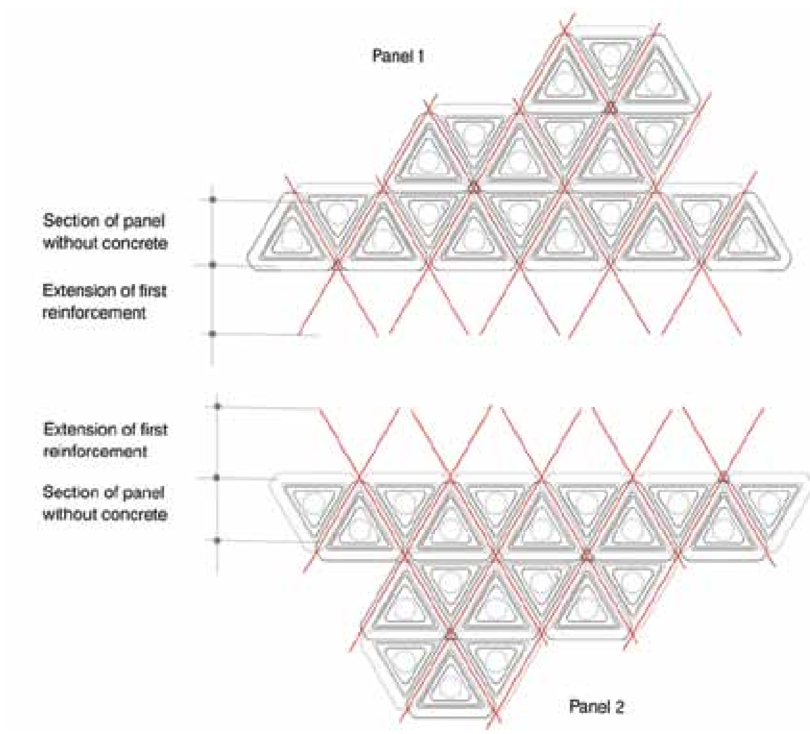


figure 7

figure 6a

Simple scaffolding on-site to receive the self-supporting panels.

figure 6b

Light equipment necessary to place the panels (< 200 kg).

figure 6c

Complete cohesive shell, with second layer of concrete cast on- site.

figure 7

Interlocking of the panels, showing the areas of panels without concrete mortar and the overlapping of rebars.

3.2 Panelization

The tessellated surface is discretized into panels, which simplify the assembly of the surface on-site. These complex-geometry panels are fabricated in a controlled shop environment using a CNC robotic arm. Fabrication follows this sequence:

1. Creation of a tessellated formwork where the pieces sit. Because the ceramic pieces are already finished, the formwork does not require a smooth surface, as needed with reinforced concrete. Two reusable formworks were studied and tested in this research: compressed sand (Figure 5a) and pin system (Figure 5b). Both tests were executed through small samples that support three to six ceramic pieces. They served to prove that the methods are technically feasible and opened a line of research for alternative formworks that will continue in the future. For the larger prototype, the formwork was made out of milled expanded polystyrene (EPS).
2. Robotic placement of the ceramic pieces over the formwork. The instructions for the robot operation were scripted to operate in a seamless mode with the tessellated surface.
3. Laying of small reinforcement bars and casting of concrete mortar between the pieces.

4 ASSEMBLY SEQUENCE

Once panels are finished, they become self-supporting components. They are placed in their final position on-site using simple scaffolding and machinery (Figures 6a–6c). Three strategies for interlocking of the panels provide structural and visual cohesiveness to the shell. First, the seam

figure 8a

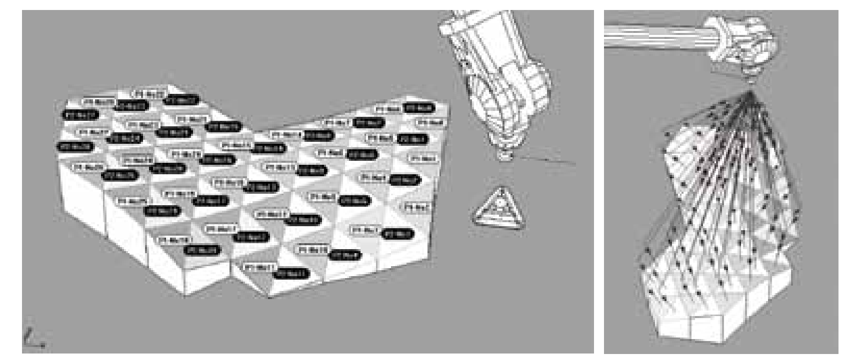


figure 8b

figure 8a

Final prototype assembly sequence.

figure 8b

Final prototype assembly sequence—digital representation.

between panels follows the same detail as between pieces, creating a continuous surface to one side and securing the space for concrete casting. Second, rebars on each panel extend to fit into the adjacent panel (Figure 7). Finally, a second thin layer of reinforced concrete is cast on-site, which locks the panels in place and allows for continuous reinforcement and post-tensioning when needed. Figure 4 shows a typical arrangement of the pieces, including the second layer of reinforced concrete that is cast on-site.

5 COMPUTATION AND DIGITAL FABRICATION

The proposed system required customization of several digital tools. The complete design-to-fabrication process was integrated in a single digital workflow, based on Grasshopper for McNeel Rhinoceros. For this purpose, several components were specially written using C# modules. Form finding was based on particle-spring systems, tested by Killian and Ochsendorf (Killian and Ochsendorf 2005). The resulting surface served as a base for tessellation of triangular ceramic pieces. This 3D information provided the input for a customized component that generated the rapid-code for the robotic pick-and-place of pieces.

6 PROTOTYPES

Several prototypes of ceramic pieces, panels, and assemblies provided material information for the development of this research project. A final full-scale prototype tested the complete design and fabrication workflow. Figure 8a shows the assembly sequence including the milled formwork,

figure 9a

figure 9b

robotic placement, laying of rebars, casting of the first layer of concrete, panel interlocking, and the second layer of concrete. Figure 8b shows digital representation of the assembly sequence. Figures 9a and 9b reveal the delicate finishing achieved in the final prototype, as well as its self-supporting capability. Figure 9a includes other experiments realized throughout the development of this construction system.

7 CONCLUSIONS, LIMITATIONS, AND ONGOING DEVELOPMENT

This study shows initial feasibility for an integrated digital design and fabrication workflow for reinforced ceramic structural surfaces. Panelization and CNC fabrication proved to be useful in reducing the need for skilled hand labor and on-site workload, the main obstacles for ceramic structural surfaces. Additionally, the research proposes two reusable alternatives to EPS formwork: sand and pin molds, both tested on a smaller scale. The final prototype proves that the proposed workflow is feasible and that the unique finishing of ceramics is a viable option today.

The ambition of the project is to develop a fully operational system capable of designing and producing lightweight and efficient ceramic structural surfaces. There are significant developments currently in progress that complement and improve the described sequence. First, a detailed structural analysis component for the complete structure and the isolated panels will support this design and fabrication workflow. Second, questions that emerged through prototyping are being adjusted, such as fine-tuning the geometry of the ceramic pieces and developing procedures for bending and laying of rebars and pouring of concrete. Finally, the on-site assembly sequence, which includes transportation, placement, and scaffolding, is being studied and will be tested on a large full-scale prototype.

figure 9a
Final prototype and tests.

figure 9b
Detail of the final prototype.

8 ACKNOWLEDGMENTS

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