Abstract. Complex brick construction is defined by its relationship to labor; it requires skilled workers in planning, manufacturing and assembly. In the modern era, this has been perceived as a significant drawback, and as such has resulted in brick construction being partially superseded by more rapid methods of fabrication, despite its inherent robustness and longevity. This paper describes the second stage of an ongoing research project which attempts to revitalize the material system of the brick special through the development of an intelligent 3D printing method that works in conjunction with a layman assembly procedure for a new class of self-supporting nonstandard brick structures. In this project, an indexed and geometrically informed jointing system, together with a parametric and digital workflow, enables rapid assembly on site without a requirement for complex site setup or skilled labor.

Keywords. Digital Fabrication; 3D clay printing; Brick Specials; Computational Design.

1. Introduction & Background

With the advent of robots in architecture, the industry witnessed a renaissance of one of architecture’s most traditional material systems - the brick. With innovative automation processes and a new approach to bricklaying, new possibilities of this ancient material came into being. Gramazio & Kohler’s early Gantenbein vineyard façade can be considered seminal in this regard, exploring the approach of automated bricklaying and its architectural potential. It is precisely this simultaneity of craft, economics, and design that is so striking (Feringa 2014). However, this process has limitations - the generic module itself is restrictive and places conditions on the formal outcomes.

Historically, architects and builders utilized brick specials in order to achieve more complex geometries within brick architecture. The brick special was particularly popular during the Gothic period and the era of brick expressionism in the Netherlands and Northern Germany, and often used to accentuate architectural features. Nevertheless, it is relatively labor intensive to produce. While standard bricks are manufactured utilizing a die extrusion process - a method that is fast
and economical, the manufacturing of brick specials has not changed over time
and involves a complex molding process, making it an expensive material to use.

In the past decade, 3d printing technology has become increasingly advanced
and has made its way into architecture. Many of the professionals in the industry
driving the development are working on full-scale production with large-scale
printers that print entire houses. Nonetheless, there is also a research trajectory
within contemporary practice that focuses on utilizing 3D printing technology to
reimagine ceramic brick specials for architectural production.

Recently, work by Ronald Rael and Virginia San Fratello has demonstrated
the opportunities presented by the non-standard module - illustrated in “Cabin of
Curiosities” (Rael and San Fratello 2017). The experimental structure utilized
ceramic 3d printing and is built from fractionally differentiated components - in
which a ceramic cladding system serves as a rain screen within a continuous
building envelope. However, the case study sidesteps issues related to ceramics
as a structural material system as it uses an additional organizational structure
to hold the components in place and therefore does not address the associated
practical challenges of ceramic processes, which center on tolerancing, shrinkage
and geometric distortion.

The “Ceramic Morphologies” project of the Material Processes + Systems
Group at Harvard GSD (Bechthold et al. 2018) begins to tackle these issues
through a digital workflow, enabling the project team to account for material
shrinkage during the drying and firing process and to construct an interlocking wall
structure. Structural performance, however, is reliant on an external custom-built
metal frame, which also acts in place of the traditional mason’s plumb line and
level - defining the spatial boundaries and configurations of the system.

Brian Peters’ project “building bytes” (Peters 2014) addresses this problem by
designing an intelligent interlocking system into the exterior skin of the 3d printed
brick module that allows for precise assembly of the components. However, the
geometric constraints of the system and the flatbed printing method involved limit
the design possibilities to only linear wall systems.

2. Objectives

The research project outlined in this paper seeks to build on this emerging work by
developing a model suitable for more complex global geometries. The project
aims to utilize the potentials offered by today’s computational and fabrication
tools to develop a system that can rely on its own structural material capacity.
Referencing a range of modular interlocking brick systems, the project provides a
more versatile solution and one that is capable of adapting more precisely to a wide
range of spatial conditions. Specifically, the following objectives were defined
for this part of the ongoing research. (1) To develop an intelligent brick special
utilizing robotically controlled ceramic 3d printing technologies with a generic
flatbed printing method that can achieve curvilinear form in the global design. (2)
To develop a brick assembly system that works without intricate jigs or specialized
tools during the assembly process, which would therefore be informed by local
spatial relationships between the neighboring bricks. (3) To further develop rapid
and automatic toolpath generation integrated within the same digital environment. Ultimately, robotic technologies provide the ideal platform for developing new fabrication processes in an experimental, iterative framework, without reinventing the machines of production (McGee and Ponce de Leon 2014). An ancillary aim of the project, therefore, was to develop an innovative, flexible brick that has the global geometry embedded within the module - one which is structurally sound, can be economically manufactured, and easily assembled by laymen.

3. Methods
To test the hypothesis outlined above, the research team developed a specific method that combined a parametric design approach for the local geometry of the brick with a digital additive manufacturing process utilizing 3d robotic clay printing in conjunction with a manual assembly system. As a testing ground, the team designed a simple 360-degree wall pavilion that was based on the idea of a torqued surface. The resultant complex surface would be difficult to construct with generic bricks, and was designed as a reference device to control the location, geometry, size, and orientation of individual brick specials.

3.1. PRINTING TECHNOLOGY
The research team utilized a standard ABB 6700 industrial robot with a deltabots linear ram extruder, equipped with a 5mm nozzle and a capacity of 5500ml specified for clay extrusions (Figure 1). As a flatbed-printing platform, the team utilized wooden boards that were placed on a single axis rotational table that works in combination with the robot. This configuration allowed for a build volume of 450mm by 450mm by 450mm. The paste-based extruder is based on a Direct Ink Writing (DIW) printing method. This method works without a secondary support material and therefore is constrained in the possible geometries that are
accurately printable. Any overhang in the design can result in deformation, thereby creating inaccuracy in the final print. The team considered these limitations by focusing on the development of relatively simple geometries rather than on more three-dimensional bricks.

3.2. DESIGN STRATEGY FOR THE BRICK AND ASSEMBLY SYSTEM

The generic brick is relatively uniform - it does not have a distinct direction for its assembly nor does it have any articulation on its faces; instead the planar faces with their specific dimensions give an essential reference when assembling them with level and plumb line and govern the overall brick bond patterns. 3D clay printing allows for variation in the brick fabrication process, while the parametric process allows us to maintain inherent geometrical and assembly relationships. The design team, informed by these factors, attempted to capitalize on the potentials offered by creating a design which maximized the articulation of the interior and exterior facades of the pavilion. To achieve this, the design team developed a brick which followed a simple c-shape in plan. While the exterior of the pavilion appears to be constructed of standardized units, the interior surface of the modules are highly individual and allow for continual variation in transparencies within the global system. This aspect also gave the opportunity to develop the system into a shading device and to experiment with light and shadows in a new way (Figure 2). In the design, each brick is both asymmetrical and slightly different in size and form; therefore it was necessary to develop an intelligent assembly system that was informed by the global geometry itself. Inspired by notching methods within timber construction that allow for a precise assembly and a tight fit of the components without any jigs, the team developed a system that was based on four integrated vertical holes in the outline of the c-shaped brick that worked as relationship indicators for the running bond. These indicators were placed where the bricks overlapped in the running bond (Figure 3). As the upper neighbor was in a different position than the lower neighbor, the indicator had to be broken in the vertical center of each brick.

As the extruder does not have the capacity to interrupt the printing process ad hoc, it was important during the brick development to generate the most efficient and continuous printing path in order to avoid undesired excess material in the final
Figure 3. brick relationship concept.

3.3. FEEDBACKS AND INPUTS

During the development of the digital fabrication strategy, the team worked via a series of feedback loops on the constant improvement of the brick design (Figure 4). Several strategies were first digitally tested, then 3D printed and evaluated following a set of criteria. With printing time, accuracy, structural performance, and material efficiency as the determining factors, the team started with the most minimal approach of fabricating a prototype by extruding just a single outline of the c-shaped brick. Troubled by the inaccuracy of the geometry, the team went on to the next iteration that was based on a truss extrusion concept. While accuracy and stability improved, the printing time increased to over eight minutes, making it an unviable solution. The team developed the brick further, eventually selecting a strategy that printed the brick with a double line and an 8mm offset. This process promised to be the most accurate and structurally sound, and also offered a reasonable printing time of six minutes per brick. To indicate the relationship within the 3D printed component to its neighbors, the team developed an indexing and jointing strategy. The team tested notching and vertical holes that worked in combination with metal bolts to align the bricks. While the former lacked accuracy and practicality, the latter proved to be a viable solution that promised precision, fast assembly and also the tolerance necessary when working with a material that behaves unpredictably at times. The final size of the holes was set to 17mm in diameter - allowing for enough flexibility for adjustments during the assembly process.

Throughout this iterative approach, several parameters in the fabrication process of the brick had to be fine-tuned in order to achieve a successful result. The key aspects were the layer thickness of the extruded clay, the operating speed of the robot and the extrusion rate of the 3D printer. The following settings proved to generate the most consistent results. The layer thickness was set to 3mm, which
resulted in the best binding in cross-section. After several tests, the motor velocity of the extruder was set at 0.15mm/s (-1500), while the TCP velocity was set to 60mm/s, which resulted in an even wall thickness of 5mm for each print. The cross-section of the double-lined wall of the brick was 15mm after firing, with a cavity of 2.5mm.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Iteration 2</th>
<th>Iteration 3</th>
<th>Iteration 4</th>
<th>Iteration 5</th>
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<td>26233 mm</td>
<td>14836 mm</td>
<td>19847 mm</td>
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<tr>
<td>Print line for one brick</td>
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<td>86.7s</td>
<td>46.7s</td>
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<td>689 gram</td>
<td>454 gram</td>
<td>570 gram</td>
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<td>Jointing and joining method</td>
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<td>bottom + top notches</td>
<td>bottom + top notches</td>
<td>bottom + top notches</td>
</tr>
<tr>
<td>Printing Path Typology</td>
<td>Single Line</td>
<td>Trench Extension</td>
<td>Double Line</td>
<td>Double Line</td>
</tr>
</tbody>
</table>

Figure 4. Consecutive brick development, quantitative analysis (top), printing path (center), prototype (bottom).

3.4. GLOBAL PARAMETRIC DESIGN APPROACH

The project team utilized a generative parametric design approach for the final prototype design to test the overall capacity of the fabrication strategy. Using Rhino in conjunction with Grasshopper, the focus within this design method was to create a flexible system that allowed for an iterative design process, testing different design versions and generating the local specificity for the brick (Figure 5). The team developed a custom-made definition that was used to create the global configuration and density of the bonding pattern that determined the incrementally differentiated individual brick. The brick pattern was based on a traditional running bond that transformed along the perimeter of the pavilion from a dense towards a sparse configuration. This set-up generated varying degrees of transparencies between the inside and the outside, transforming the bricks from a “squeezed” to a “stretched” c-shape. Each digital brick was based on poly-surface geometry, which was translated into layered line geometry for printing by a custom-made grasshopper script. For the code generation of the ABB robot, the research team used the HAL-Plug-in for Grasshopper. The software allowed for the efficient and accurate translation of line geometry into target planes. All bricks were automatically translated into ABB Rapid code with 1539 target planes each. For the entire project, the team generated approximately 1.5million lines of code.
4. Results

4.1. PAVILION FABRICATION

Over a period of 22 days, the research team printed the 882 individual bricks needed for the construction of the pavilion. Around 700 kg of standard low fire terracotta clay (P1331, Potterycrafts ltd) was used for the fabrication of the bricks. There were approximately 264 print files with three or four bricks per file. All files were manually nested for the 450mm by 450mm print board. Though the size and geometry of each brick varied, the printing time for each brick was, as predicted, six minutes on average. As all bricks were different, the team had to develop a method to index them individually. The team utilized a method they had previously developed for another project that was based on an indentation mark. In this case, a date stamp was used to mark each brick with a specific date that correlated to a particular position in the pavilion. All bricks were air-dried at room temperature on drying racks for at least 48 hours to minimize any deformation in the firing process. While the clay has a firing range from 1020°C - 1180°C it was found after several structural tests however, that firing the bricks at 1125°C gave stronger and more economical results (Cone 02). All firing was done in a standard electric kiln. After firing, each brick weighed approximately 600 grams, resulting in an overall weight of 530kg for the structure that measured 2.2 meters in height and approximately 2.7 meters in diameter.

4.2. ASSEMBLY

For the assembly process, the lightweight bricks were shipped in boxes to site. The labeled bricks were organized systematically and then assembled in four days (Figure 6). Each brick was first placed in its dedicated position to test its accuracy. Using the relationship indicators and the metal bolts, each brick was then bonded to its neighboring parts. The system with four indicator holes turned out to be quite accommodating during the assembly process, providing enough tolerance to assemble the system precisely. Though the manual brick laying process was effective and relatively fast, the research team allowed enough time for the bonding agent to dry. There was concern that the overall assembly would be negatively affected if the construction method was too rapid as the geometry of the pavilion had overhangs.
4.3. REFLECTIONS

The outcome (Figure 7) of the project was successful regarding the architectural exploration, the design process, the 3D printing process, and the overall assembly method. However, during the assembly process, several issues arose that need further consideration in future iterations. Though all bricks have a relationship to each other, the accurate assembly of the prototype was ultimately based on the precise positioning of the first row. As the terracotta material shrinks approximately 11% when fired at 1125°C, the global form in the digital file had to be scaled accordingly in order to produce an accurate template for the positioning of the initial layer. While the shrinkage of the material is relatively even in all directions, the drying and firing process can result in distortion of the individual brick in multiple directions. Though deformation can happen during the drying and firing process and depends on an even consistency of the drying environment and the position of the brick in the kiln during firing, there seems to be one additional parameter that plays an important role. After comparing several fired bricks with the original outline of the digital information, it became apparent that the distortion is dependent on the specific geometry of the brick. Bricks with wider angles deformed slightly more than bricks with narrower angles.

As a consequence, the location of the indicator holes changed unevenly across the bricks. Hence, there was a discrepancy between the digital information and the physical information. Although the team had incorporated relatively large tolerances in the indexing system of the individual bricks, which eventually compensated these errors, there was no certainty at the start of the construction as to whether the prototype would be a success or failure. It is essential for the future development of the system to better understand the relationship between material, geometry, printing path, printing thickness, drying process, firing process, and the resultant occurring deformations. This could be achieved through a more systematic testing procedure that would focus only on these aspects. In this respect, some of the scanning and finite element analysis methods developed through the “Ceramic Morphologies” project by the GSD for evaluating the precision of the fabrication method could be a starting point for further improvement (Bechthold...
et al. 2018).

Figure 7. Overall Assembly of Prototype.

5. Conclusions

The described 3d ceramic clay printing methodology in this paper can be seen as a viable fabrication technique to revitalize brick specials for contemporary architectural practices that focuses on specificity in brick construction systems rather than uniformity. However, future iterations should incorporate additional aspects into the brick design, and also the assembly strategy to improve the overall system.

Currently, the structural performance of the individual brick was tested only through a low-tech method. To further improve the design, future iterations should incorporate a more intelligent and systematic approach that allows for active feedback during the design development. This method could include testing via plug-ins such as Karamba or other structural software, in combination with the testing of the compression strength of physical prototypes via standard devices. It is anticipated that this method could eventually lead to more material-efficient solutions.

The current design focused mostly on a visual transformation of transparencies along the perimeter of the pavilion. Ultimately, the system has proven to perform as a viable solution for shading membranes. In light of applying such a system on a larger scale, the utilization of software packages such as ladybug or ecotech could provide more differentiated information for the design of the overall assembly and also the design of the individual brick.
A further aspect that could be developed in future iterations is the articulation of the brick through the development of the printing process itself. Though the DIW method has its limitation, the fact that this method includes the design of the printing path could lead to innovative explorations within this territory. The testing of opportunities and limitations of the printing method could make the process a more integral part of the design and could allow for unique design expression and novel material textures. This development would allow for designs that can be continuously differentiated and address varying conditions in architectural solutions. Oliver van Herpt has done similar explorations in his “Functional 3D Printed Ceramics” project. As technology has always been a driver for architectural expression, we need to test the limits to find appropriate solutions for our contemporary but also future built environment.

A final aspect to improve in future iterations is one of the most significant barriers to the more general application of the outlined construction system and is found in the complex assembly logic, logistics and the on-site management of a large number of fractionally differentiated components. The identification and organization of the individual bricks throughout 3D printing, firing, shipping, and construction processes coupled with breakage and the discussed deformation of individual units creates a wide range of challenges.

One strategy to address this would be to minimize the number of unique components or to develop nested families. However, since the objective was to test the potentials offered by the specific tailoring of each unit this approach was not considered in this case. Yet, a real-time scanning system, which recognizes parts and aids with sorting and assembly coupled with an intelligent user interface, would help to make this system a more viable on-site solution and could expand the application beyond experimental prototypes and pavilions. Recent developments in augmented reality, both in terms of hardware such as Microsoft HoloLens and software packages such as Fologram could be integrated into the workflow to make the system more effective. In its ability to identify physical parts this system could be implemented both during production as a means to sort and organize and during construction to facilitate accurate assembly.

References