The Pennsylvania State University

The Graduate School

Department of Architecture

INTERLOCKING CONSTRUCTION SYSTEM OF 3D PRINTED CLAY COMPONENTS

A Thesis in

Architecture

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2019

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ABSTRACT

With the rapid population growth in urban areas, the demand for housing is constantly increasing. Due to land scarcity, there is a trend to demolish existing low-rise buildings to replace with high-rise ones. This deconstruction process produces a considerable amount of non-recyclable waste that is harmful for the environment.

The goal of this research is to develop an interlocking construction system where the construction components can be assembled without the use of mortar and disassembled without producing waste. 3D printing enables the fabrication of bespoke designs with intricate details and varying material properties. In this research, I explore design and fabrication strategies for 3D printing interlocking construction components using clay. I present 1) design alternatives for interlocking construction components that are suitable for 3D printing, 2) strategies for 3D printing the construction components using different tools and materials, and 3) a system to assemble the construction components into small-scale housing units.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I am deeply obliged to the following individuals and institutions that helped made this thesis possible:

Jose Duarte, Shadi Nazarian and Benay Gürsoy Toykoç for their advice and support in the development of this research in computational design. Their critiques, thoughtful conversations and encouragement made this thesis possible. I also thank Tom Lauerman for his enlightening advice about additive manufacturing with ceramic clay and support in 3D printing.

The Department of Architecture for supporting my graduate education and the Digital Fabrication Lab of the Stuckeman School for helping with technical support.

My fellow colleagues and friends at the Stuckeman Center for Design Computing and at the Stuckeman School, for their help and support.

My mother, for her words of encouragement and unconditional love.

Muhammad Shamim Hasan, my husband, for believing in me and supporting me with his unlimited encouragements at every step of the way.

Chapter 1

Introduction

Research Scope and Aim

Rapid population growth in urban areas increase the demands for new housing units, as well as the modification of existing ones prompted by the changes in household needs. Due to land scarcity, there is a trend to deconstruct existing low-rise buildings to replace with high-rise ones. This deconstruction process produces a considerable amount of non-recyclable waste materials that are harmful for the environment. The intention of this research is to create a construction system of interlocking blocks that can be easily assembled without the use of mortar and then disassembled. The idea is that buildings built with these interlocking blocks can be deconstructed without producing much waste and the deconstructed blocks can be reused for future constructions. In addition, the use of these interlocking blocks can enable the residents to easily modify the layouts of their houses according to their needs.

With additive manufacturing technologies, it is possible to fabricate bespoke designs that have intricate details and varying material properties. In this research, design and fabrication strategies are explored for 3D printing interlocking construction components using clay. This allows the fabrication of construction components that are not possible to obtain with conventional methods, such as casting and extrusion. Moreover, it enables the mass customization of interlocking construction systems where the construction components with unique shapes, sizes and textures can be fabricated without the need to create unique formworks for the production of each individual unit.

Although various interlocking construction components have been developed and used since 1970's, these are mostly designed to be filled with concrete/mortar and need reinforcements. Thus, the existing interlocking construction systems are not entirely mortar-less, and the final products are not suitable for easy deconstruction or reuse. Furthermore, there are few explorations to 3D print interlocking construction components that can enable mass-customization. This research extends the state of art by proposing the use of 3D printing technologies to fabricate interlocking construction components that do not need mortar or any supporting structure to be assembled. With this aim, this thesis presents 1) design alternatives for interlocking construction components that are suitable for 3D printing, 2) strategies for 3D printing the construction components using different tools and materials, and 3) a system to assemble the construction components into small-scale housing units.

Thesis Paper Outline

The following chapters will describe the process followed in the design and making of the proposed 3D printed clay components for the interlocking construction system.

Chapter 2 lists and compares past and present examples of interlocking construction components. Consequently, previous research on robotic fabrication, computational design and construction, and additive manufacturing of ceramic bricks are presented.

Chapter 3 demonstrates the step-by-step research methodology of the research. This research is divided into three major stages - interlocking component analysis, interlocking component design for different connections, and guidelines for block design, system development and customization. This chapter illustrates these three stages of the research in detail with diagrams.

Chapter 4 describes in detail the design and fabrication explorations for interlocking construction components. It presents the various 3D printing strategies employed to fabricate the construction components using different tools and materials.

Chapter 5 illustrates the rules for designing and generating the interlocking construction components as well as the rules for their assembly into a small-scale housing unit. The possibilities for customizing the construction components are also demonstrated through parametric design explorations.

Finally, Chapter 6 summarizes the research and identifies its limitations. It also presents potential future research steps and scope.

Chapter 2

Literature Review

This chapter presents a review of existing interlocking construction systems and the use of additive manufacturing in the construction industry.

Interlocking Construction Component

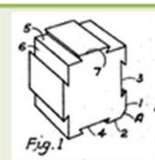
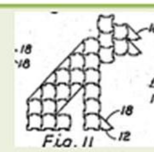
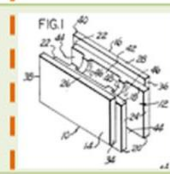
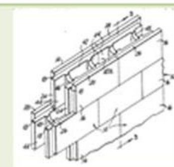
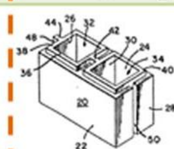
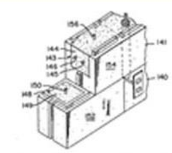
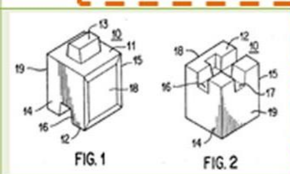
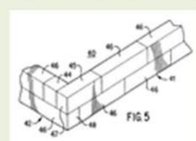
Interlocking construction components such as building blocks have first appeared in the toy industry. A very popular example is 'Lego'- a toy set of interlocking bricks. The concept of Lego came from the toy named "Automatic Binding Bricks", which was patented in 1939 (by Harry Fisher Page) and released in 1947. Two years later, in 1949, a more complex version of this interlocking building block was patented by James G. Blackinton independently (Blackington, 1949). This new block was designed with interlocking dove-tail ribs and grooves on its sides and on its cross-sectional contour, which allowed certain new and useful geometrical characteristics (Table 2-1). According to Blackinton, this interlocking block toy would allow open exploration of imagination by creating dynamic geometric shapes as desired.

Eventually, this interlocking block toy concept was applied to real building construction. Franz Julius Gergely invented a hollow building block in the form of a parallelepiped that had corrugated or saw tooth-shaped on its upper and lower surfaces (Gergely, 1977). This invention allowed the block to be stacked easily to construct a straight wall and then to pour mortar/concrete into the aligned hollows (Table 2-1). One year later Sanford Pearlman invented an improved version of this block (Pearlman, 1978). Pearlman's block was made of aggregate material and had better interlocking details in both vertical and horizontal directions (Table 2-1). His block was also designed to be stacked easily without mortar joints, but with a nicer appearance, like normal brick walls. Besides, the horizontal and vertical cavities inside the block were designed in an interlinked way so that the added concrete from the top of the wall could flow both in the horizontal and vertical directions. About one decade later, Gary N. Hanson and Keith W. Inness designed a simplified version of this interlocking block with two rectangular hollows within each rectangular block, which allowed the blocks to be connected both horizontally and vertically (Hanson and Inness, 1991). In addition to pouring the cement from the top of the wall, they also designed the provision for adding reinforcements along with electrical conduits (Table 2-1).

Although these interlocking building blocks were claimed as mortar-less, they needed the hollows to be filled out with concrete for proper strength, as their interlocking parts were not designed to be self-supported against lateral force. However, in late 90s multiple solutions were proposed, which did not need any concrete filling for structural strength. Emidio J. Forlini introduced solid interlocking blocks with larger interlocking parts (Table 2-1), (Forlini, 1997). Robert James Mork and Robert John Mork designed a mortar-less interlocking system of hollow blocks by using a separate horizontal bar to keep multiple blocks together as well as to hold the upper layer of blocks (Table 2-2), (Mork and Mork, 2000). Similarly, Pieter A. VanderWerf invented a vertical locking system for hollow concrete blocks by introducing locking channels on the smaller sides of a rectangular block to be locked with a separate slender vertical locking bar (Table 2-2), (VanderWerf, 2001).

The interlocking construction components described above were designed to construct simple and straight rectilinear walls using rectangular blocks. However, in early 90s, Cornelis Beerens designed six-faced symmetrical cubic interlocking blocks, which interlocked by 1, 2 or 4 quarters of each face to construct the desired structure (with a relatively complex shape) by connecting an unlimited number of blocks (Table 2-2), (Beerens, 1992). In 2005, George R. Miller introduced polyhedral interlocking construction components to construct relatively more complex and innovative structures (Miller, 2005). This block (Intercleaving Spatially Dichotomized Polyhedral Building Blocks and Extensions) was designed to serve as building block, structural element, and so on (Table 2-2). Recently, Yevgeniy Pavlovich Kuzmin, invented interlocking spatial components of various shapes, allowing the same shape to interlock arbitrarily in various directions, orientations and sides to create a variety of dynamic and complex structure as desired (Table 2-2); (Kuzmin, 2013). Adám Bálint designed a pinwheel shaped interlocking construction component derived from an equilateral triangle to be used as building block, paving unit, tile or toy (Table 2-2), (Bálint, 2015).

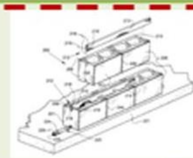
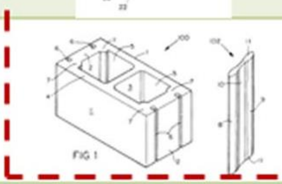
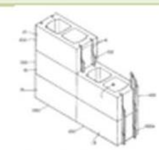
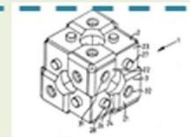
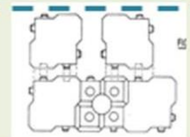
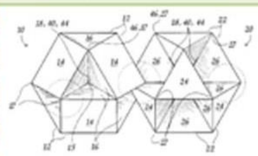
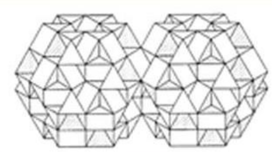
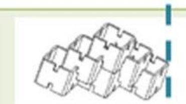
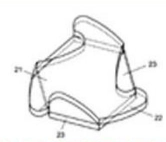
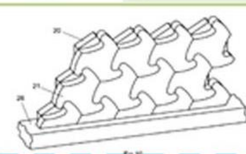
Table **2-1**: Interlocking construction components from 1949 to 1997.

Year of invention	Name of Inventors	Interlocking Components	Interlocked shape
1949	James G. Blackinton		 
1977	Franz Julius Gergely		
1978	Sanford Pearlman		
1991	Gary N. Hanson and Keith W. Inness		
1997	Emidio J. Forlini		

Filled up with concrete/mortar and reinforcement BAR

Table **2-2**: Interlocking construction components from 2000 to 2015

Connected with another component

Year of invention	Name of Inventors	Interlocking Components	Interlocked shape
2000	Robert James Mork and Robert John Mork		
2001	Pieter A. VanderWerf		
1992	Cornelis Beerens		
2005	George R. Miller		
2013	Yevgeniy Pavlovich Kuzmin		 
2015	Adám Bálint		

Complex geometry

The interlocking construction components invented from 1939 to present were designed for construction processes involving manual labor. The assembly process becomes more complex as the complexity of the shape of the interlocking blocks increases.

Automated Construction

In this section, I have considered two aspects of automated construction: one is robotic construction and other is computation in design and construction. Regarding robotic construction I am interested in exploring robotic assembly, tool selection and tool path design. The tool is the part that is attached to the robotic hand to hold and assemble the construction component, also known as the end effector. Tool path is a digital drawing produced in a program designed to control the movement of the robot. I have explored the computation in design and construction using some examples to explore how computation and virtual analysis have been done by others for different geometrical shapes as well as material properties.

Robotic Construction

Recently, there has been an increased interest in the automation of construction process, using robots on different scales to perform different tasks. Gershenfeld, Carney, Jenett, Calisch, & Wilson in their paper "Macro fabrication with digital materials: Robotic assembly" introduced the notion of digital materials (virtually modeled materials) and discussed their usage and implications. They described the production of discrete parts, the modeling of the complete structure using those parts and their automated assembly by robots (Gershenfeld, Carney, Jenett, Calisch, & Wilson, 2015).

Gramazio & Kohler in their book "Made by robots: challenging architecture at a larger scale" explored the challenges in making non-standard materials and in using non-standard construction processes in large-scale architectural projects (Gramazio & Kohler, 2014). In addition, they demonstrated the possibilities of robotic construction processes in the design and construction of high-rise buildings.

Shirinzadeh, Alici, Foong & Cassidy in their article "Fabrication process of open surfaces by robotic fiber placement" discussed the potential of robotic fiber placement techniques in composite materials for open surfaces relatively time consuming and expensive traditional manual construction method (Shirinzadeh, Alici, Foong & Cassidy, 2004). They described the procedure (simulation-based fiber path generation, fiber steering, and sensory-based contour following methodologies) through the demonstration of three different techniques of fiber placements.

In the article "Robotic fabrication of acoustic brick walls" Vomhof, Vasey, Brauer, Eggenschwiler, Strauss, Gramazio & Kohler described the automated process of making and assembling acoustical bricks step by step, to create a wall using a robot (Vomhof, Vasey, Brauer, Eggenschwiler, Strauss, Gramazio & Kohler, 2014). In this example, the aim of their research project was to create an economical solution for an acoustic wall inside an office space by taking advantage of automated construction processes, while adding aesthetic quality and flexibility of customization (Figure 2-1 and 2-2).

Figure **2-1**: Robotic fabrication of acoustic brick walls

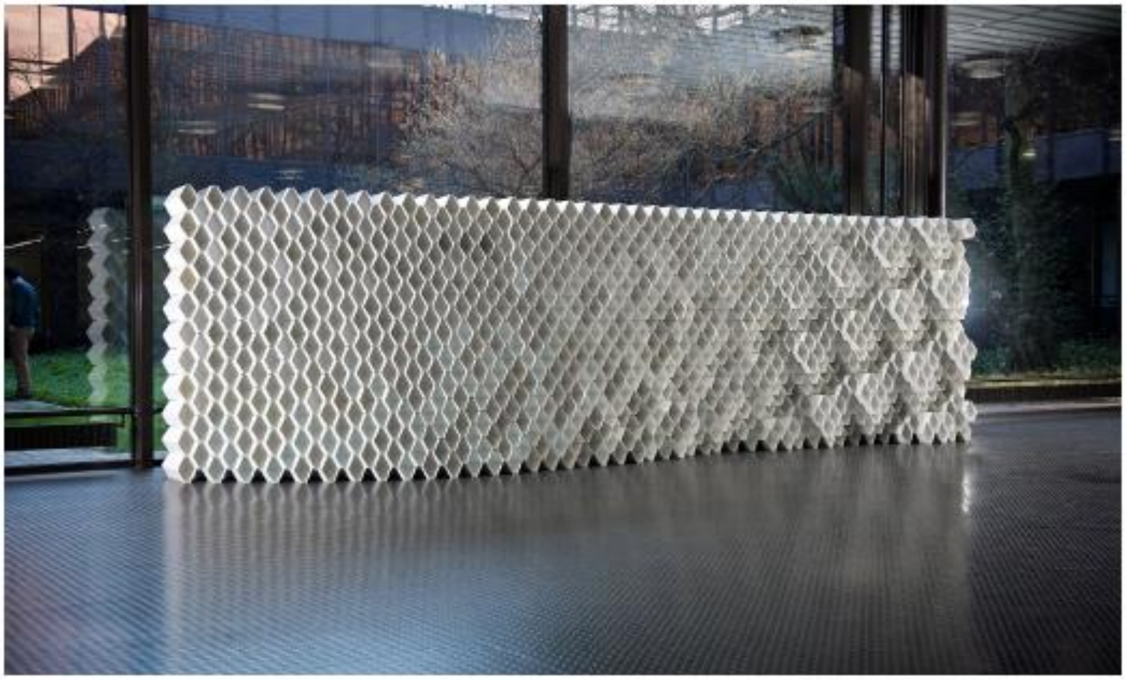


Figure **2-2**: Robotic fabrication of acoustic brick walls – completed work

While the first article, “Macro fabrication with digital materials: Robotic assembly” addresses digital modeling and robotic assembly, the third one, “Robotic fabrication of acoustic brick walls” is more focused on material construction. The second article, “Made by robots: challenging architecture at a larger scale” is focused on large-scale non-standard design and construction processes using robots. Finally, the last one presents a complete automated wall construction process, which shares some similarities with the proposed research, but using different material. Overall, although these examples do not directly refer to the automated construction of interlocking construction components, they are very useful to understand robotic assembly and construction processes, while being helpful to provide basic directions for the proposed research.

Computation in Design and Construction

Exploration and analysis of design and construction through computation, programming, and virtual modeling has introduced a new dimension in architectural and construction sectors. It is very efficient to analyze a large number of possible solutions and select the best practices for real-world construction based on virtual simulation, which can closely mimic and bring to attention the complexities presented in the real situation. In addition, this process saves time, recourses, labor, and cost, as it enables the study of various methods of construction and assembly of parts to find an optimum solution. The articles and research examples that follow address the implementations of such computational processes in design and construction.

Ceccato in his article "Material Articulation: Computing and Constructing Continuous Differentiation" talks about the importance of rationalization of geometric form, constructability and function through computation for mass-customized industrial production (Ceccato, 2012). Demonstrating certain projects of Zaha Hadid Architects, his article tries to bridge the gaps between contemporary design and construction using computational construction processes.

Menges, in his article "The New Cyber-Physical Making in Architecture: Computational Construction" portrays the impacts of cyber-physical production systems in architecture (Menges, 2015). He explores the new challenges brought about by emerging technologies for building construction as well as for the design of form, space and tectonics.

Willmann, Gramazio, Kohler & Langenberg, in their article "Digital by material" discusses digital materiality – the synthesis of data and materials (Willmann, Gramazio, Kohler & Langenberg, 2013), demonstrating the analytical development and application of digital materiality in architecture along with a new expression and material sensuality.

In their research paper "Material swarm articulations - new view reciprocal frame canopy", Pantazis & Gerber demonstrate a complete process of constructing a canopy structure made by slightly bent interlocking plywood boards (Pantazis & Gerber, 2014). The main intention of this research was to enable a detail computational and virtual analysis of the design of the shape of an interlocking board and of its construction process before the real construction took place. To accomplish their goal, they started with the analysis of the shape of single unit and then assembled this unit in various ways to get multiple types of canopy structures. Later, they analyzed the selected structure in terms of material properties and the self-load behavior using a computer program in Grasshopper to find the most suitable solution to be built in reality (Figure 2-3 and 2-4).

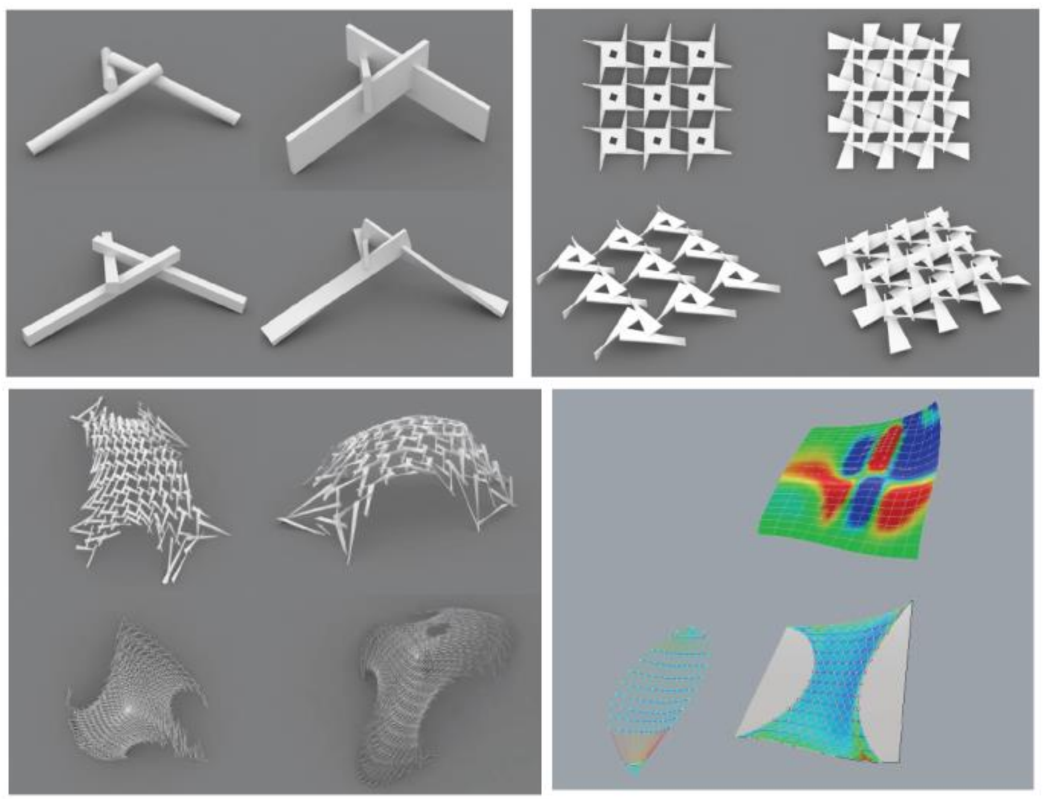


Figure **2-3**: Computational analysis before the real construction of canopy structure

Figure **2-4**: Reciprocal frame canopy after construction

While the first essay focuses on the rationalization of geometric form in contemporary architecture, the second one shows how the understanding and thinking of making form, space, and tectonics in architecture are facing challenges due to emerging technologies. The third essay is more inclined towards the combination of digital data and the physical expression of materiality. Finally, the last one shows the step by step computational analysis used to build a small-scale structure with interlocking components. Because the final structure was built using manual labor and a variety of materials, I find it particularly useful because it is close to my own research regarding the use of virtual simulation procedures. As a whole, the study of these explorations helps me understand the role that computational construction processes may have in the real world in the future. In addition I find them helpful in structuring the framework of computational analysis for my research.

Additive manufacturing with ceramic materials

Additive manufacturing with ceramic materials is becoming increasingly popular in craft and artistic production. There are open source projects to develop 3D clay printers. It is important to note that there are not, however, many studies that explore 3D printing of building blocks using ceramic materials.

Figure 2-5 shows an example of 3D printed ceramic clay bricks (Bechthold and Craig, 2017). These bricks were designed and printed by Harvard University GSD team for an indoor pavilion construction. The whole process was computationally controlled, from design to manufacturing. Each brick has a slightly different geometry to fit on the structural metal frame. Though, this is a temporary structure and these bricks are not self-supported or interlocking components, this research provides a valuable precedent to better understand the conceiving and making 3D printed interlocking clay blocks.

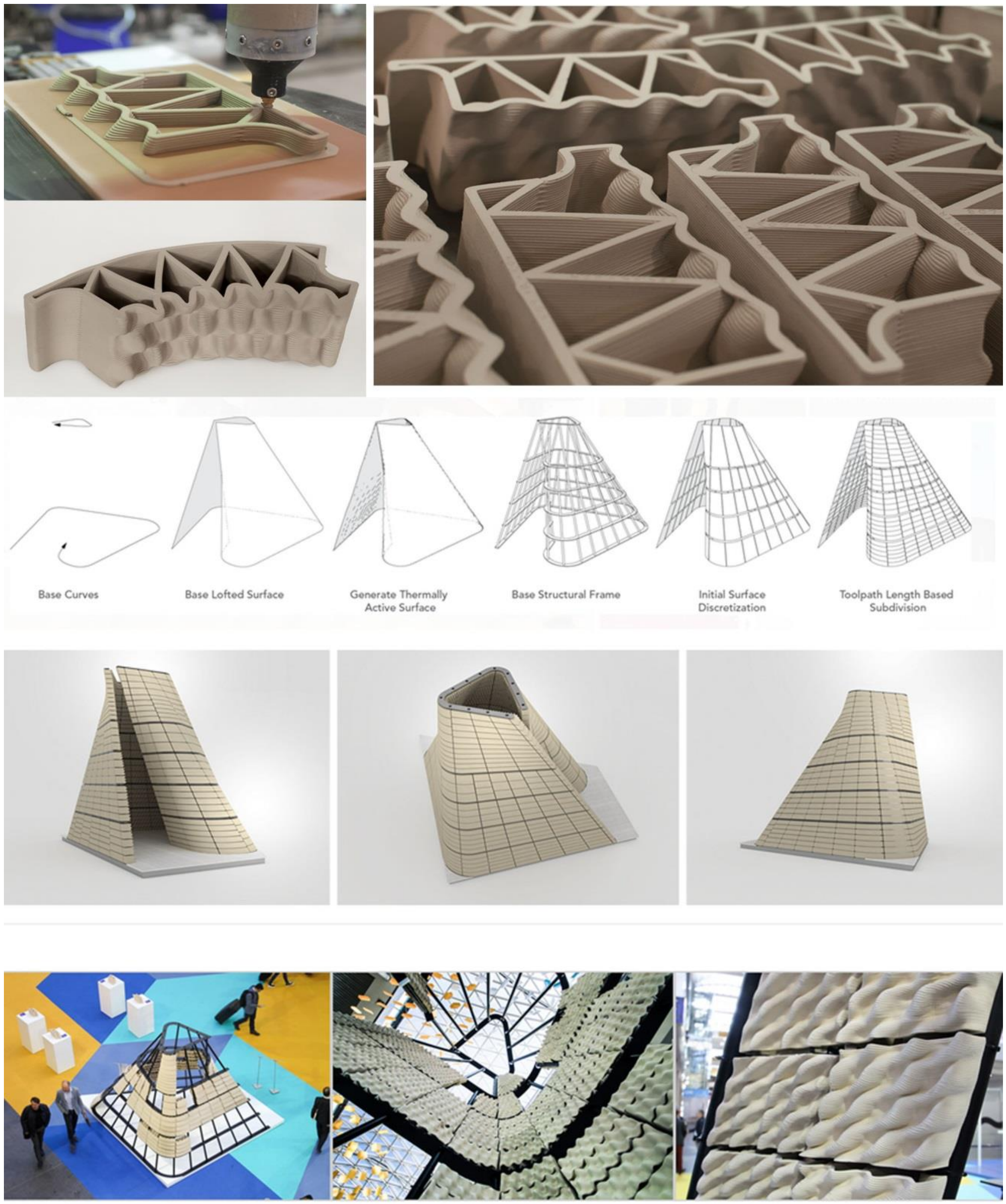


Figure **2-5**: Ceramic Morphologies_Cevisama Installation 2017_Harvard Graduate School of Design

Chapter 3

Methodology

This chapter describes the research framework, which is divided into two major parts – Design and Making (figure 3-1). The design stage involved the exploration of various forms that were suitable for interlocking construction and could be printed, as well as the design of the tool path for 3D printing them. In this stage the geometry of interlocking components for various wall connections and surfaces was explored. In this regard, initially seven types of interlocking blocks were designed considering different types of connections (figure 3-2) – straight wall connectors, L- and T-shaped connectors for walls, and L- and T-shaped connectors for wall to roof and wall to floor. The design stage was guided by multiple variables, including material deformation during printing and after drying, printed layer dimensions, printing tool path geometry, length and scale of printing in relation to material setting time, printing without formwork, and so on.

In the making stage, these digitally designed blocks were physically tested. The preliminary testing material was PLA (plastic) filament used for 3D printing functional prototypes, using a conventional 3D printer. The final goal however was to 3D print the blocks with ceramic clay using a customized clay printer. A series of tests were designed and undertaken to test the manufacturability of designs. The results of these tests provided guidelines to optimize the shape and size of the interlocking construction components, as well as the appropriate setup for printing them. Furthermore, the results of this process were analyzed to extract generic rules for the design and making of similar interlocking blocks, as well as for their assembly into a housing unit design (figure 3 – 3). At the end, the results were evaluated to identify potential benefits and limitations, as well as future research steps.

The processes of design and making were interdependent in terms of geometry, tools and materials. This interdependency was considered during the explorations mentioned above. For instance, the geometry of the interlocking blocks was not simply designed through abstract representations, but rather relied on the materials and tools used for 3D printing. Based on the analysis of the printed outcomes, further modifications were introduced regarding digital design, material selection, and tool settings.

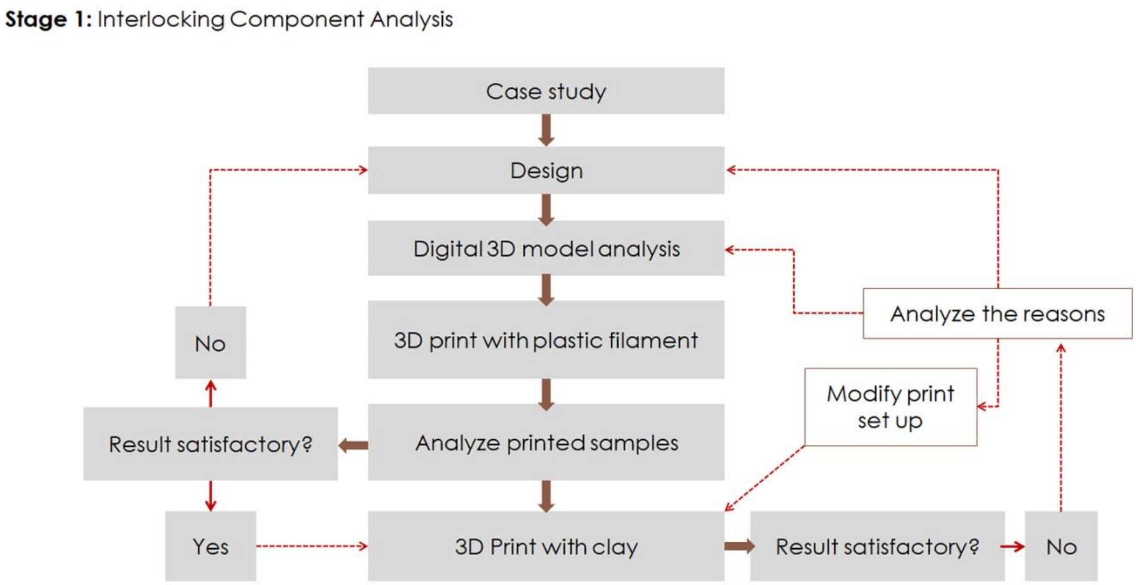


Figure **3-1**: Diagram showing the method followed in the design and analysis of the interlocking components.

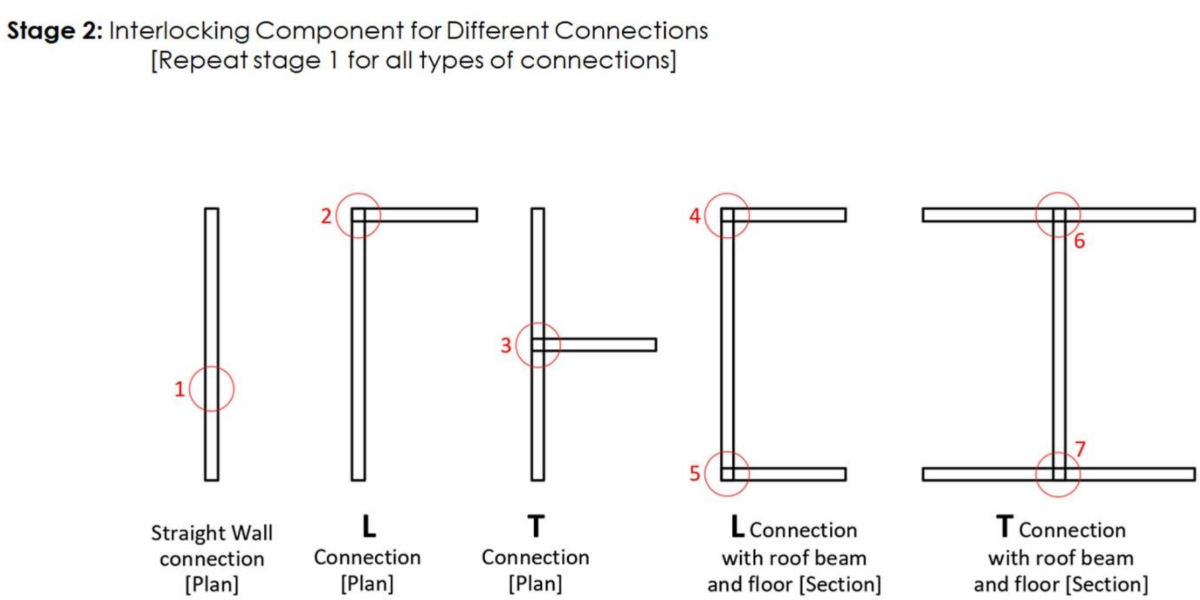


Figure **3-2**: Diagram showing the various types of connections between construction elements considered in the design of the interlocking blocks.

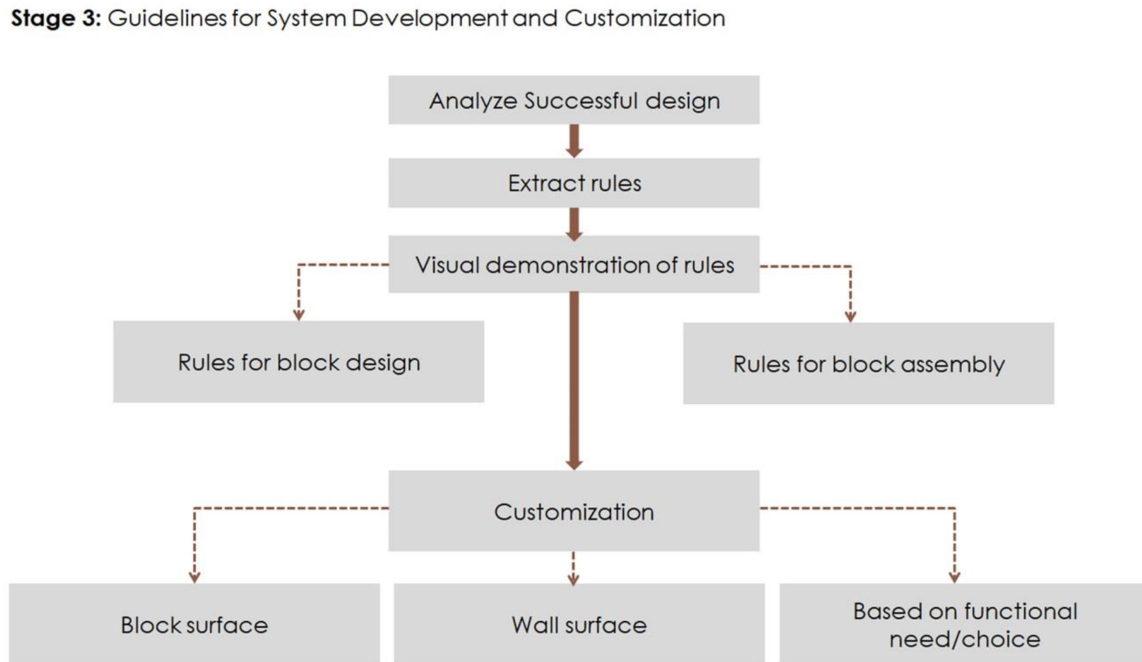


Figure **3-3**: Diagram showing the method followed in the development of the system and the customization guidelines.

Chapter 4

Experiments and Analysis

This chapter presents the step by step experimentation that was designed and undertaken to accomplish the final research goal. The experimental results will also be analyzed regarding failures, partial successes and successes to understand the reasons behind them and develop solutions to achieve better optimal results. The experiments began with the digital design of interlocking blocks, followed by their fabrication, which involved multiple printing tests using different materials and tools. At the end, modified design options were proposed based on the analysis of these tests.

Digital Design and Analysis

The design of the blocks was guided by two major concerns: how the blocks would interlock with each other and how they would be printed. Multiple blocks were designed using Auto CAD and Rhinoceros with different interlocking systems. Figure 4-1 and figure 4-2 show these blocks' interlocking system, their printing orientations, and the resulting wall structures. Several types of blocks, named A through F, were designed. Type A was included with a triangular notch system for interlocking in the vertical and horizontal directions. The resulting structure is a curve wall with parametric texture, arranged in a grid pattern. To avoid the weak vertical joints in type A due to the grid arrangements, type B was designed to arrange a typical stretcher bond system for the brick wall. Here, the interlocking system used a rectangular notch for both vertical and horizontal interlocking, following the block's rectangular geometry. Additionally, these blocks were designed to be used as exterior planter blocks in the construction of a vertical wall garden. Types C, D, E and F were designed to construct simple straight walls and focused on aspects of printability. Type C was designed with a combination of extended triangular shaped interlocking parts with a top to bottom hollow triangular geometry to be interlocked with other blocks. This was intended to keep block arrangement flexible according to need and choice. Type D was designed considering lateral forces on the wall. Here, the mirrored interlocking geometry, without any notch, helps to resist lateral loads from both sides of the wall. However, type D needs a support system during printing. Therefore, to avoid the need to both print the support and later remove it, types E and F were designed in a simplified way. Unlike the previous block types, types E and F were designed to be used together in the construction of a straight wall following the stretcher brick bonding arrangements. Similar to type D, types E and F were also designed with an interlocking geometry without any notch that helped resist lateral loads from both sides of the wall. The next step was to 3D print the blocks to test their feasibility and effectiveness.

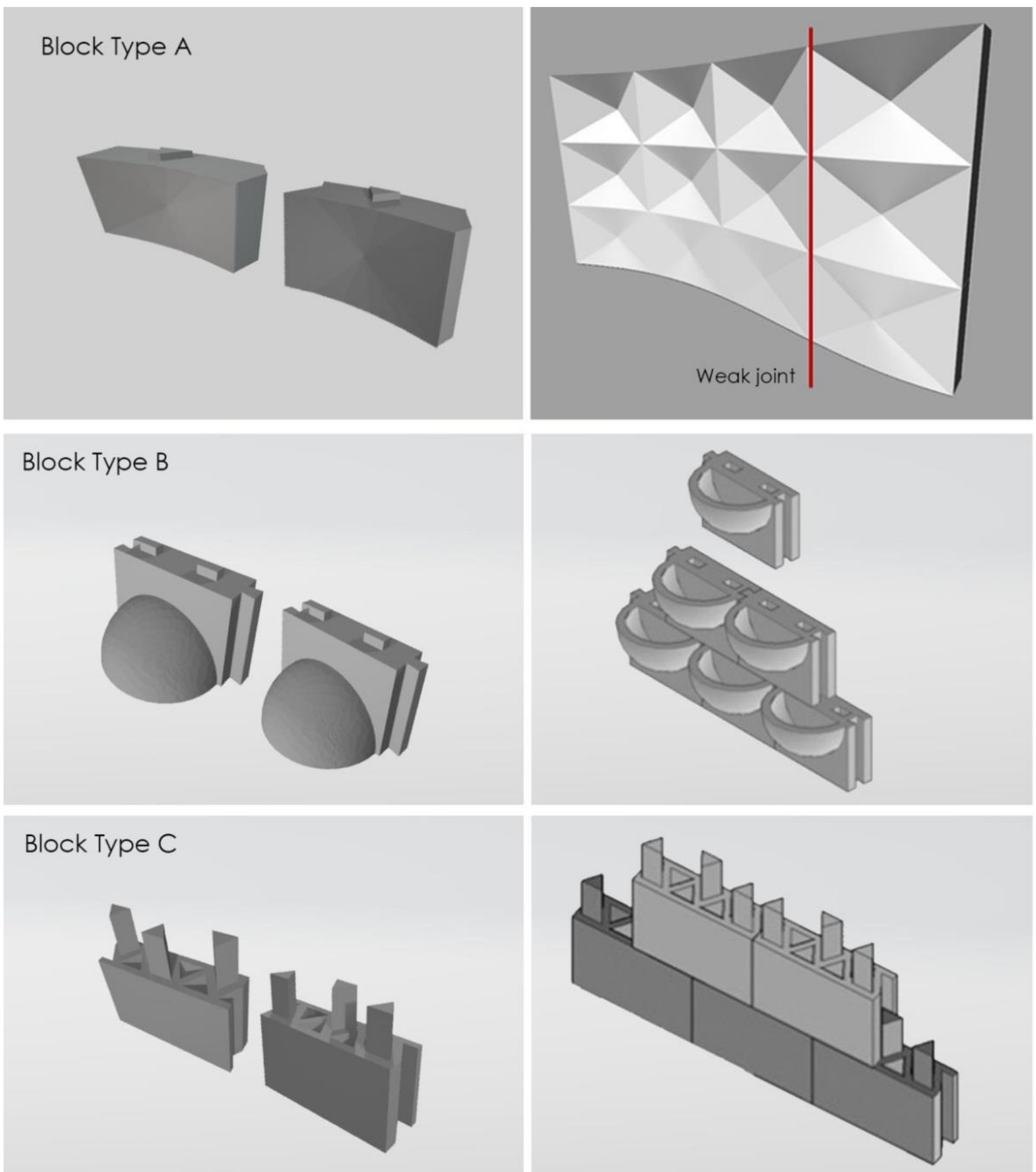


Figure **4-1**: Digital design of block types A, B and C

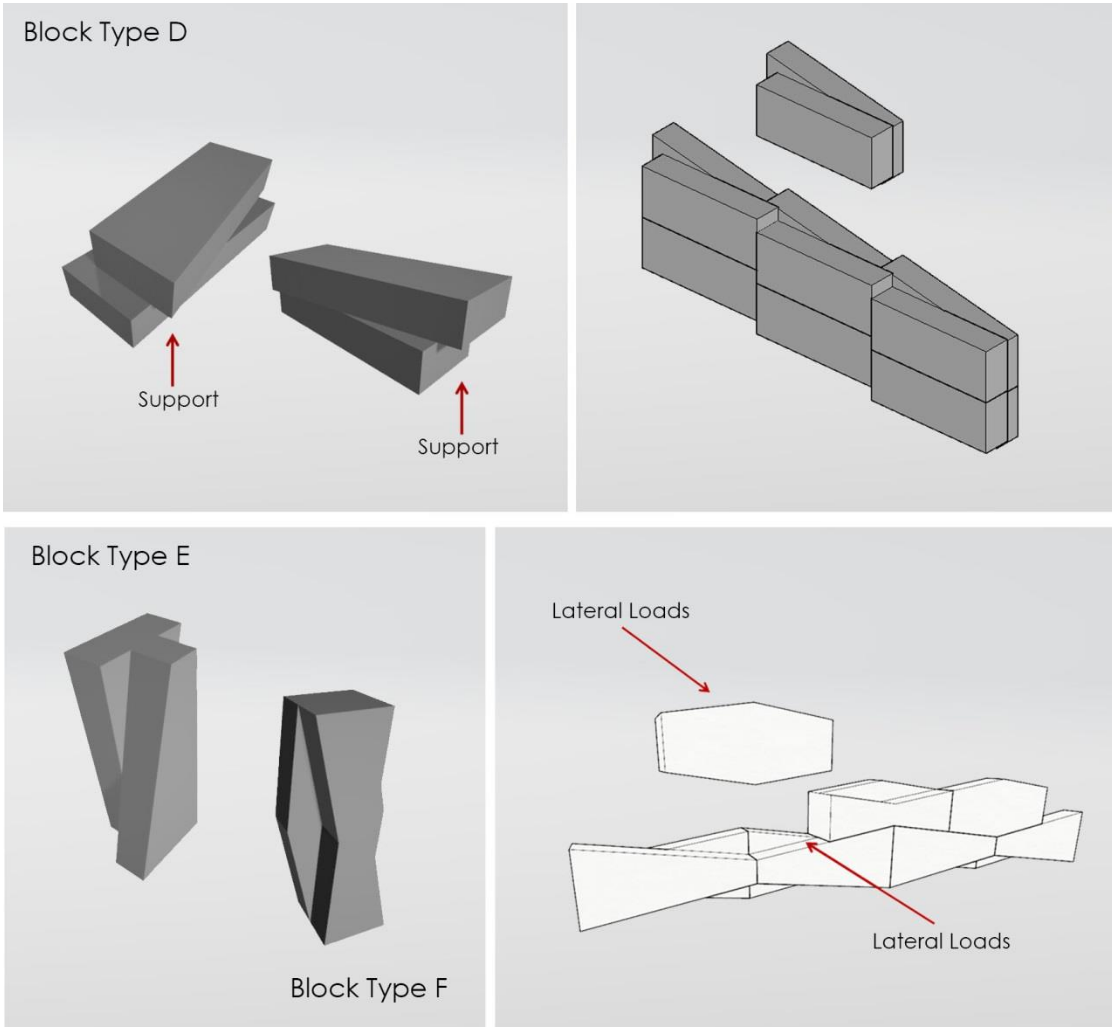


Figure **4-2**: Digital design of block types D, E and F

3D Printing Experiments and Analysis

3D printing experiments were conducted with 3 different materials - PLA filament, concrete and finally with terracotta clay, using different printing tools.

3D Printing with PLA Filament

Before proceeding to concrete or clay printing, the desired final materials, all the blocks were 3D printed in plastic using Original Prusa i3 MK2/3 printer with PLA filament, to test the interlocking system's feasibility. Figure 4-3 shows the blocks printed at a reduced scale. These printed samples demonstrated that the joints between type A jointed were very weak; those between type B and C were very strong, working well for small scale plastic printing, but did not constitute a suitable interlocking system for concrete or clay blocks; type D had the potential to work for concrete and clay, but needed supports during printing; type E and F were suitable for large scale printing with concrete or clay, without any support structure. Therefore, types E and F were selected for the printing tests with concrete and clay.

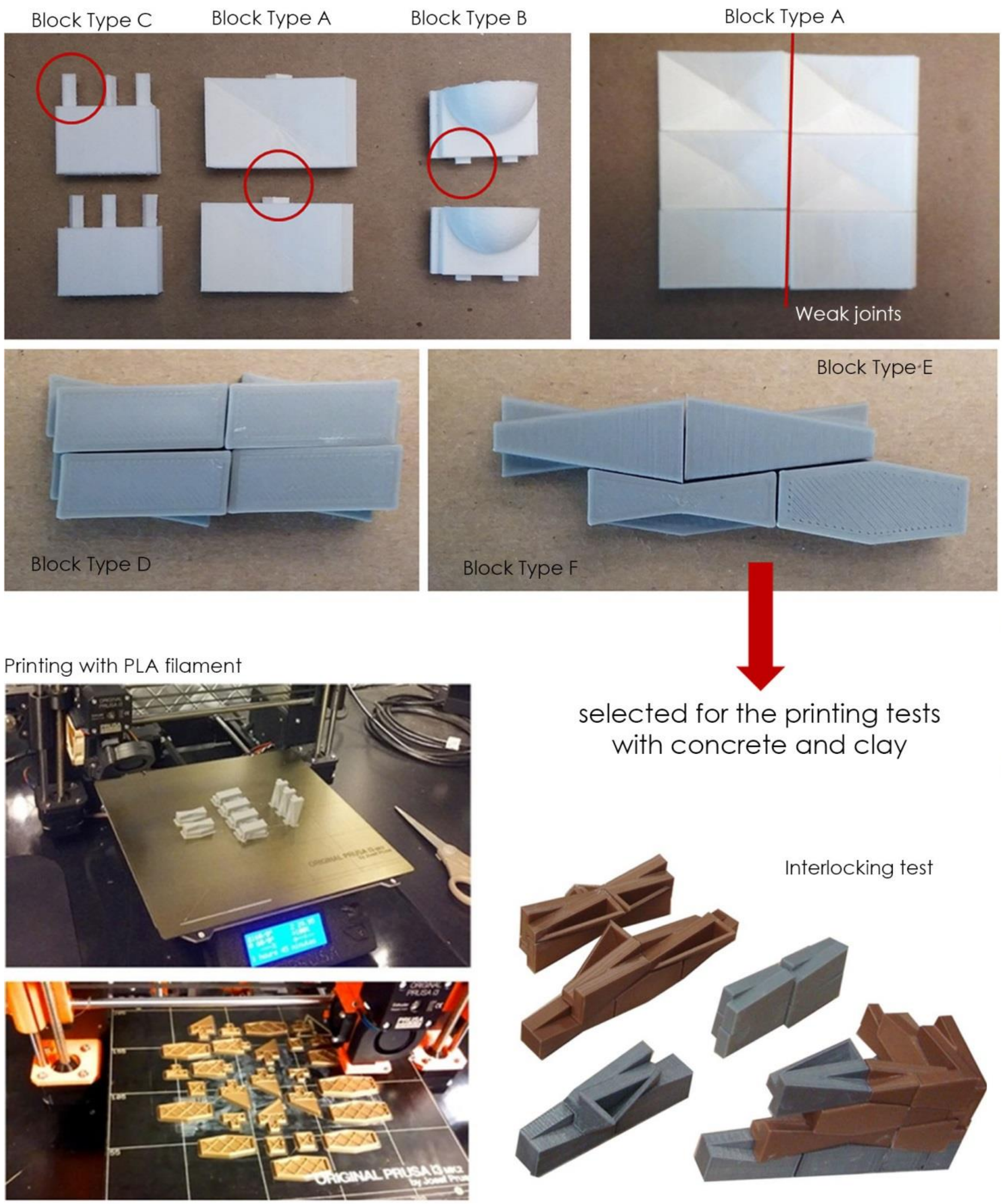


Figure **4-3**: 3D Printed blocks using PLA Filament at reduced scale

3D Printing with Concrete

For concrete printing a modified version of type F block was selected. This is the base block with flat bottom surface for wall construction. A 6-axis ABB Robot was used for this purpose. A customized printing tool (a 10mm diameter nozzle) was attached to the robotic arm. An automatic concrete mixer and pump (Duomixer) was used to pump and extrude concrete through the nozzle during printing. Figure 4-4 shows details of this robotic printing. First, the block's digital model was sliced to produce a tool path, which is a continuous line used to guide the robotic arm's movement. The toolpath was produced using Hal Robotics and then fed to robot controller. Several attempts were made to print the block. In the first attempt, the sample collapsed during printing after reaching two-thirds of height. In subsequent attempts, two more samples were printed. The first slumped when two-thirds of the height had been printed and consequently printing was halted, while the second also slumped, but only at one-fourth of the height. The first example deformed significantly, but did not collapse and the second example was less deformed and more stable. Despite slumping, it was possible to observe all the printed samples. They were considerably heavier than typical concrete blocks or bricks. Also layer heights were too large and the resulting surfaces were too irregular, and therefore, not suitable for interlocking. This exploration revealed some important limitations of robotic printing with concrete. Concrete needs time to cure and this was the main reason for collapsing and the deformation. As the block was too small in size, there was not enough time for bottom layers to cure enough to support top layers. To make it possible to 3D print small scale concrete blocks, it would require modifying the robotic printing system by using a smaller nozzle and adding admixtures to accelerate curing right before extruding the concrete. Adding accelerators to the dry mix or water would not work because concrete would harden too early and clog the hose. In these experiments, changing the printing system was not an option, so further experiments were conducted with clay 3D printing, which shares characteristics with concrete printing, but is more suitable for small scale, higher resolution printing.

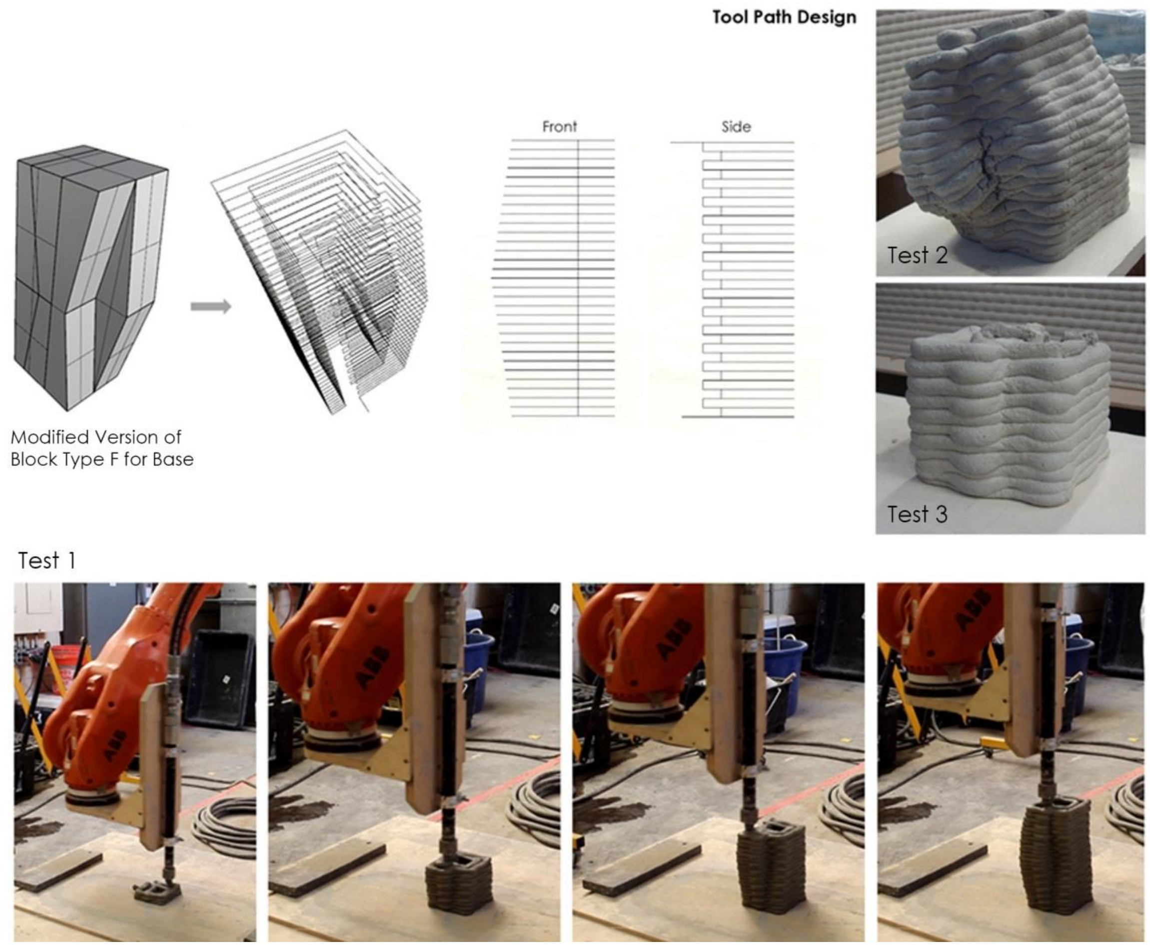


Figure **4-4**: 3D printing with concrete using 6-axis industrial robot

3D Printing with Clay

Printing experiments with clay were conducted using two different customized clay 3D extruders. To facilitate discussion, let's name these two printers Printer A and Printer B (Figure 4-5). Printer A was assembled by Benay Gürsoy Toykoç (Assistant Professor, Department of Architecture, Pennsylvania State University) following open source online instructions and printer B was developed by Tom Lauerman (Associate Professor, School of Visual Art, Pennsylvania State University), and is being developed as an open source design. This printer, costing approximately $3000, requires a very complex assembly process, which is not yet documented as the printer is still evolving. When we decided to use this printer, it had already been used successfully to print many forms with clay, with capabilities very similar to plastic printing. Unlike an industrial robot, both of these printers can use g-code for movement instructions generated from open source 3D slicer software. In this regard, Cura was used for printer A and Slic3r PE was used for printer B. The major differences between these two printers concern how they move and how the clay is pushed through the nozzle. Printer A has a fixed printing bed and the extruder moves along three axis (X, Y & Z), and clay is pushed with an air compressor. In printer B, the printing bed moves along X and Y directions and the extruder in Z direction. In addition, printer B has a mechanically actuated clay pushing system rather than an air compression system and can be controlled digitally via software rather than relying on an analog pressure regulator. Printer B uses a piston to push the clay through the nozzle, which is fully synchronized with the printing software, allowing for volumetric extrusion which is repeatable and less dependent on clay moisture content.

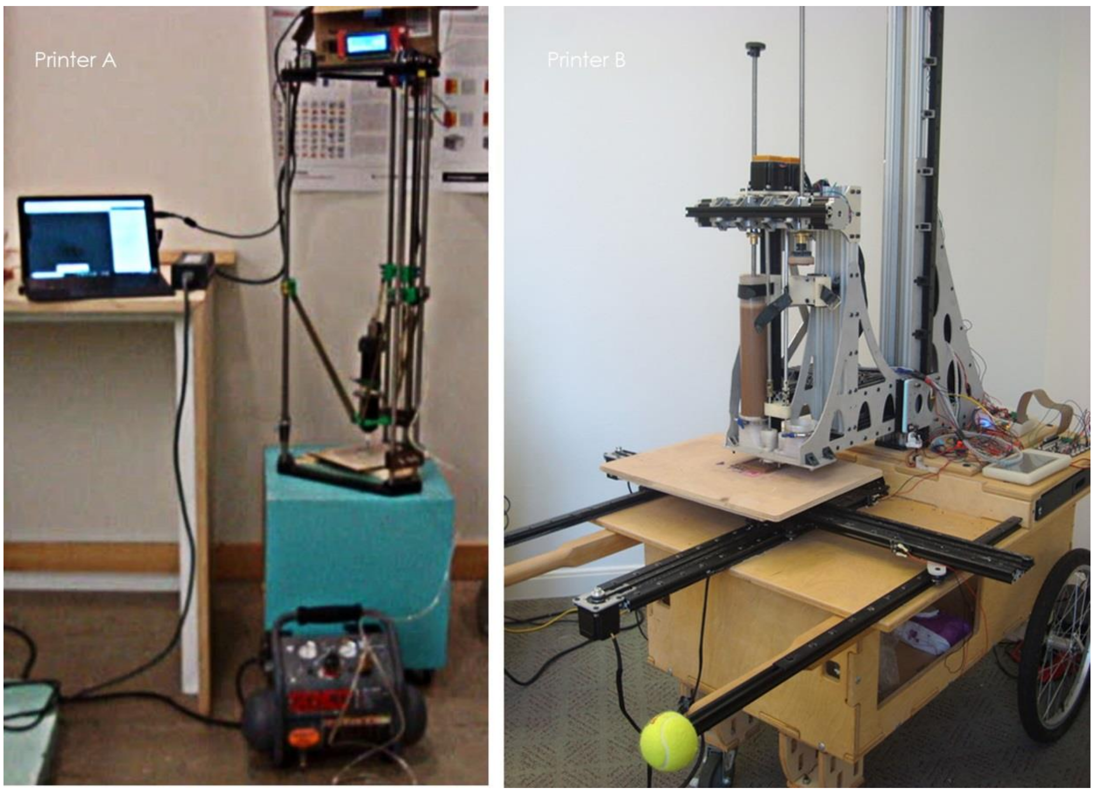


Figure **4-5**: Customized 3D clay printer

Test with Printer A

Figure 4-6 shows some samples printed with printer A. These test prints were resulted from explorations aimed at finding suitable printing settings for the printer, considering the following variables:

1. Print Speed
2. Nozzle Diameter
3. Layer Height
4. Infill Speed
5. Infill Density

Table 4-1 presents data for all the11 tests performed. Tests 1 through 6 show the journey toward successful printing. Test 7 and 8 were two successful printed samples for small scale straight wall surface. However, for large scale printing, the surface wall will need internal structural support, called 'infill'. Initial attempts (test 1 to 3) to print with the default infill system generated by Cura were not successful. Two explanations for these failures were raised: they were due to the discontinuity of the printing tool path, when it was printing the infill system, or the default infill printing speed, which is faster than the surface wall printing speed. When the infill printing speed was faster, it caused disruption in printing the infill layers, as the manually controlled air compressor was not compatible to push the clay through nozzle in two different pressures at the same time. As this printer can successfully print, when it is a continuous surface, therefore, one option could be design a customized infill toolpath as a continuous surface, and another option could be find out a suitable infill printing speed that is well synchronized with the surface wall printing speed and the pressure rate of the air compressor. Hence, Test 9 to11 were conducted to find out what happens when the infill printing speed is equal or less than the surface wall printing speed, which is usually between 30 to 60 mm/s for clay printing. The test result (test 11) shows that this printer can successfully print with infill system generated by Cura, when the infill printing speed is half of the surface wall printing speed. The only limitation of printer A is that it uses an air compressor to push the clay, which is very difficult to control in terms of finding the proper pressure given the density and viscosity of the clay, and time it according to the printing time.

Table **4-1**: Printing set-up record for Printer A

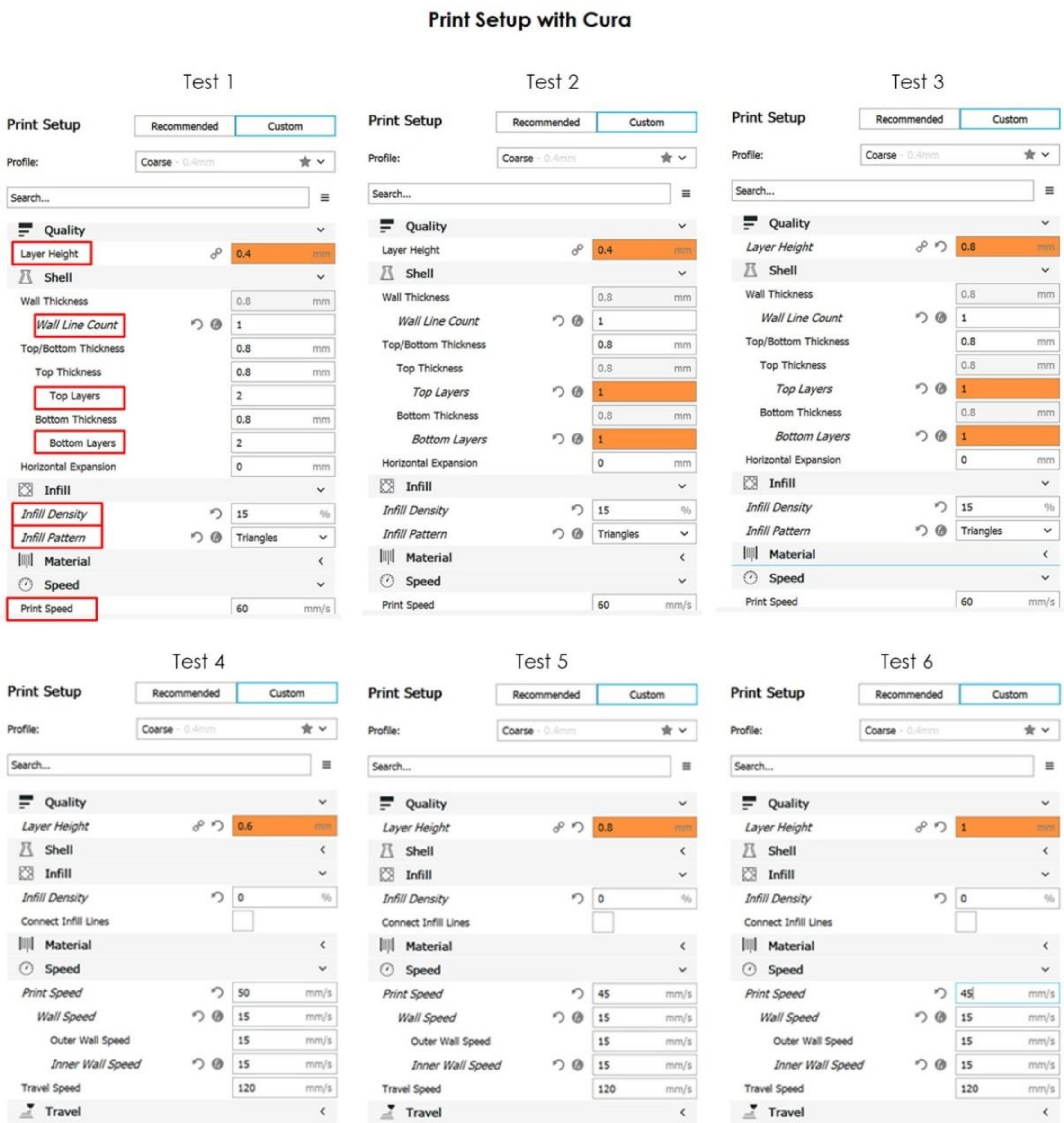
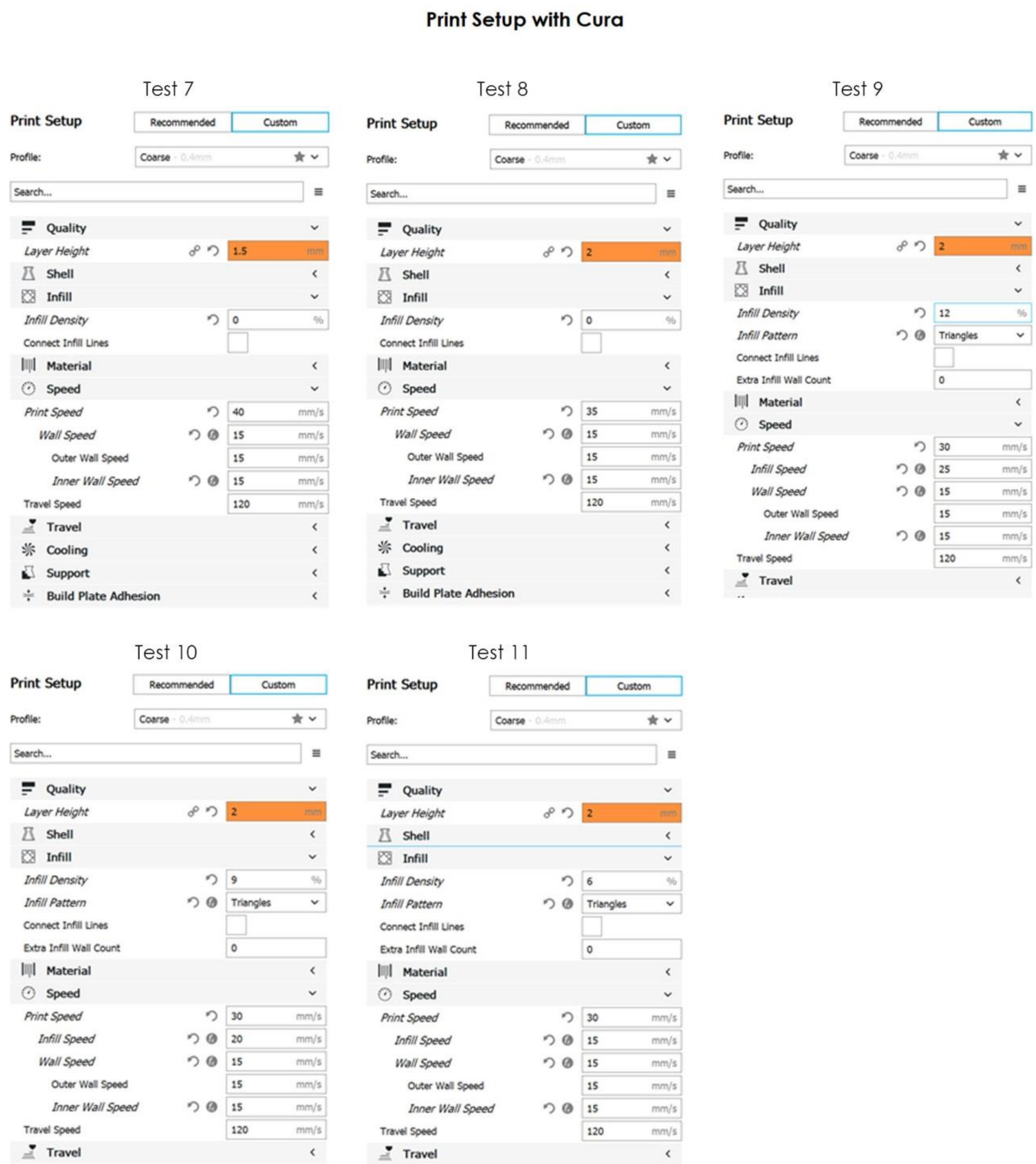


Table **4-1** (continuing): Printing set-up record for Printer A



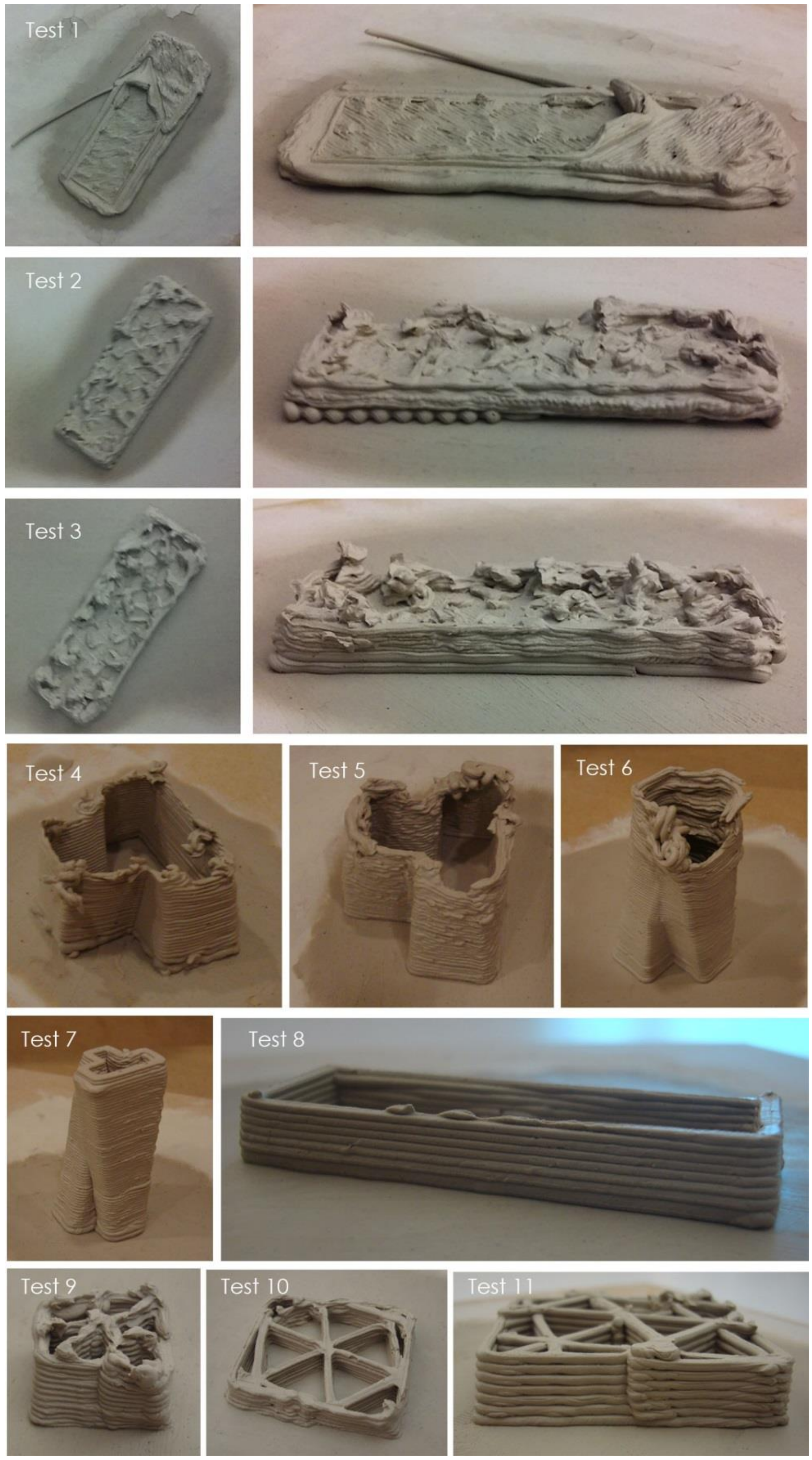


Figure **4-6**: Test samples printed with Printer A

Test with Printer B

Suitable printing settings for printer B had already been tested by Tom Lauerman and, therefore, it was not necessary to conduct further tests for this purpose. This printer was thus selected to print in real scale blocks type E, F as well as a modified version of type F. Printing tests were conducted for these blocks, considering three different orientations of the blocks (figure 4-7). Figure 4-8 shows the samples printed with printer B. Terracotta Earthenware clay was used for this printing, which can be fired with relatively low temperature (max. 1160 °C). Terracotta, which translates roughly to "baked earth", is widely used in architecture throughout the world. It is abundant, inexpensive, and easy to manipulate. Deformation rate of Terracotta can vary, but examples of formulations developed for architectural applications are optimized for minimal deformation, typically via the addition of aggregate materials including sand and calcined clay. The water content of the clay was approximately 25%. In these tests, the variable values used for printing with printer A were used as following for printing with printer B. Print Speed – 40mm/s

1. Nozzle Diameter – 2.85mm
2. Layer Height – 1.5mm
3. Infill Pattern – Triangle
4. Infill Density – 30%
5. Firing Temperature – 900 – 950 °C

A record was kept about how much the block shrank after firing (Table 4-2). Results show that the shrinkage rate was between 6% and 10%. The shrinkage happens uniformly in all directions. Therefore, it will not have any impact on the interlocking system, but must be taken into account to generate an accurate block size after firing, by making the digital model larger than the desired scale.

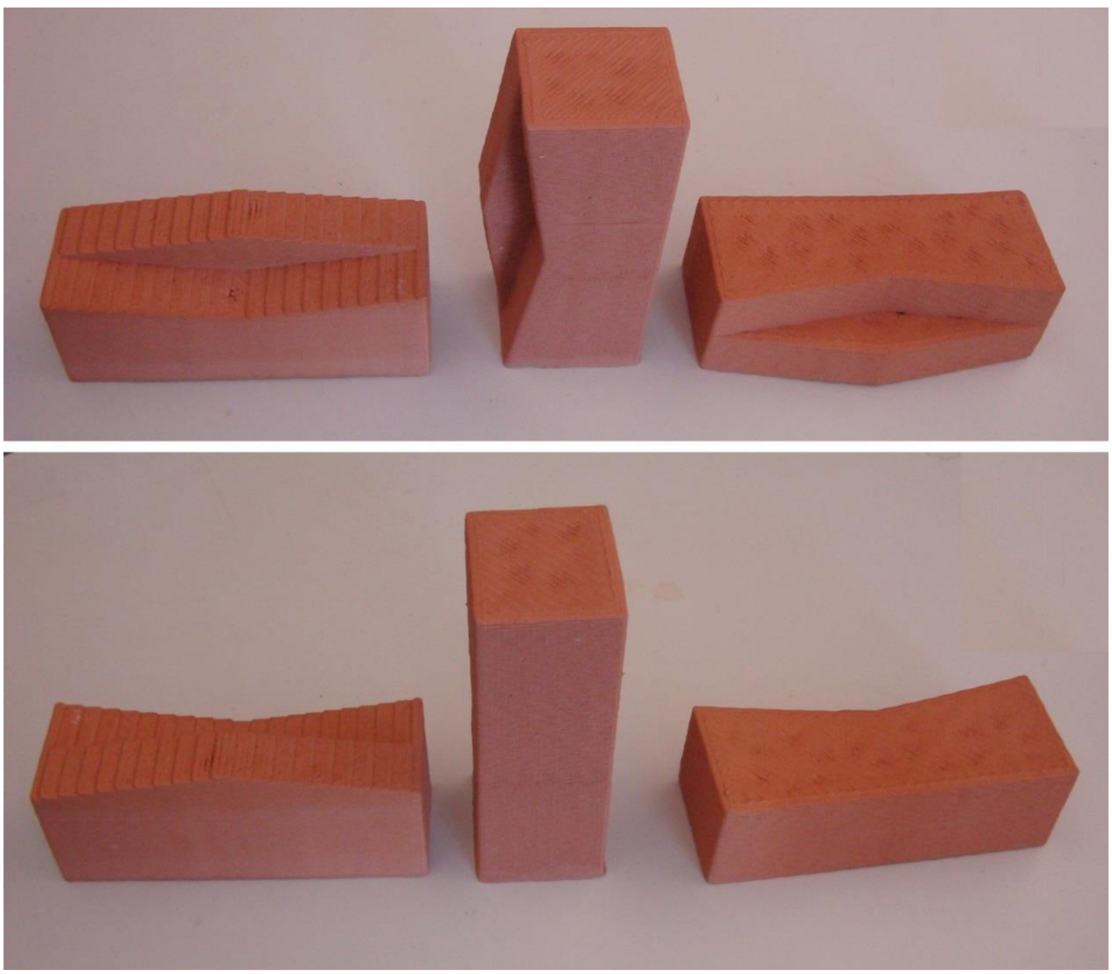


Figure **4-7**: Printing orientation tests

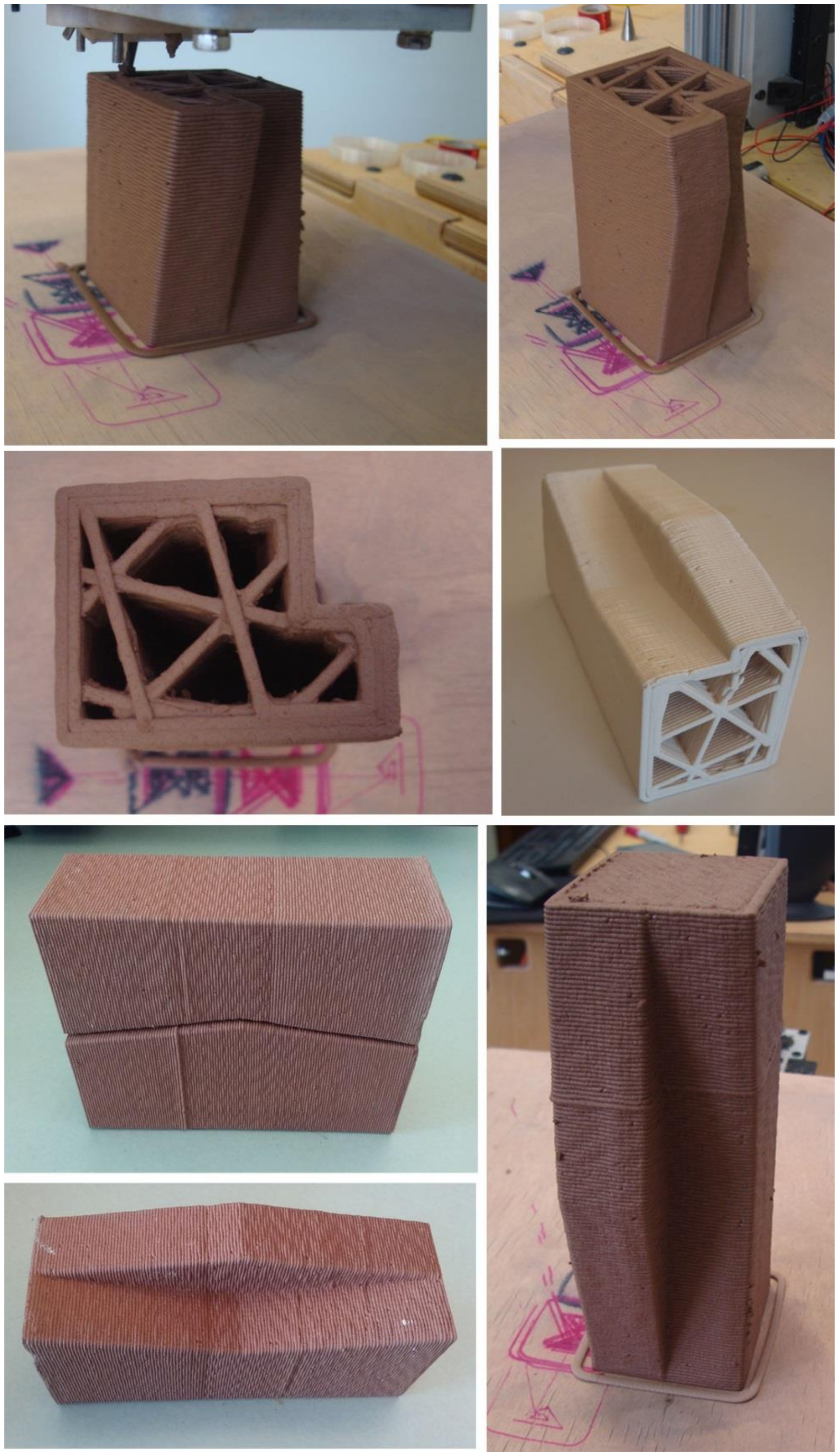
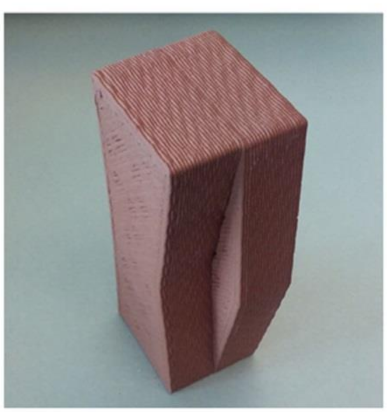


Figure **4-8**: Samples printed with printer B

Table **4-2**: Records showing shrinkage rate after firing

	WET			FIRED		
	Height mm	Width mm	Thickness mm	Height mm	Width mm	Thickness mm
1	200	90	66	185	85	60
2	200	90	66	178	82	60
3	200	90	70	180	80	60

Shrinkage 6 to 10%


Block 1


Block 2


Block 3

Figure **4-9**: Assembly of printed samples with printer B

Chapter 5

Guidelines for System Development

This chapter describes the rules followed in the design and fabrication of the proposed interlocking construction components, and shows how to assemble these components to construct a house. These guidelines are codified as a set of rules that were inferred through analysis of the process followed in the development of the system and of the experimental results described above. These rules can be followed in the parametric design of blocks that have the same kind of interlocking system as the one developed.

Rules for Block Design

Figure 5-1 shows the rules followed in the design of the interlocking blocks for making straight walls. The rules describe how the final blocks were designed by using simple trapezoids and parallelograms to create complex three-dimensional, interlocking shapes.

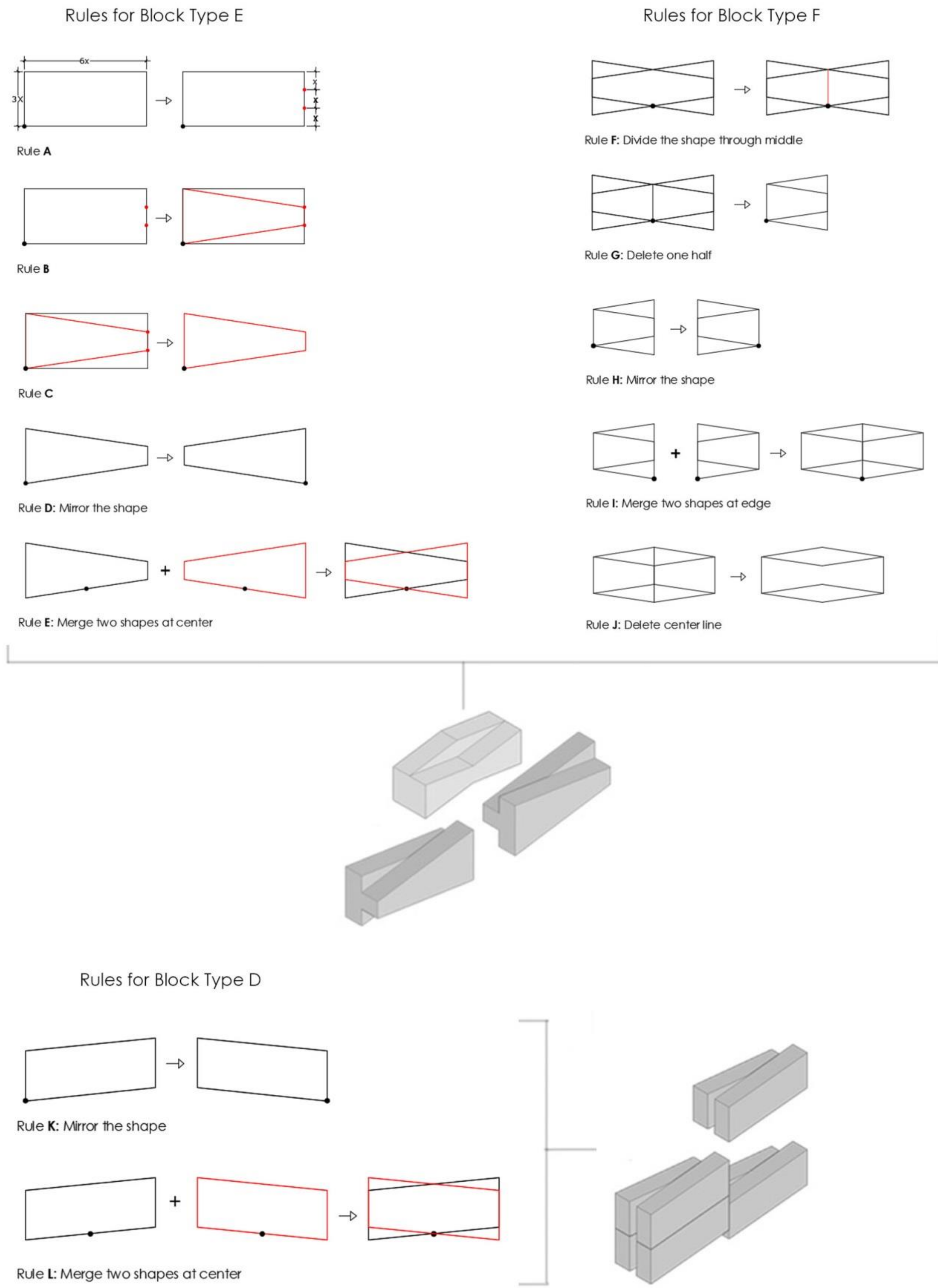


Figure **5-1**: Rules followed in the generation of the proposed interlocking blocks

Straight Wall Assembly

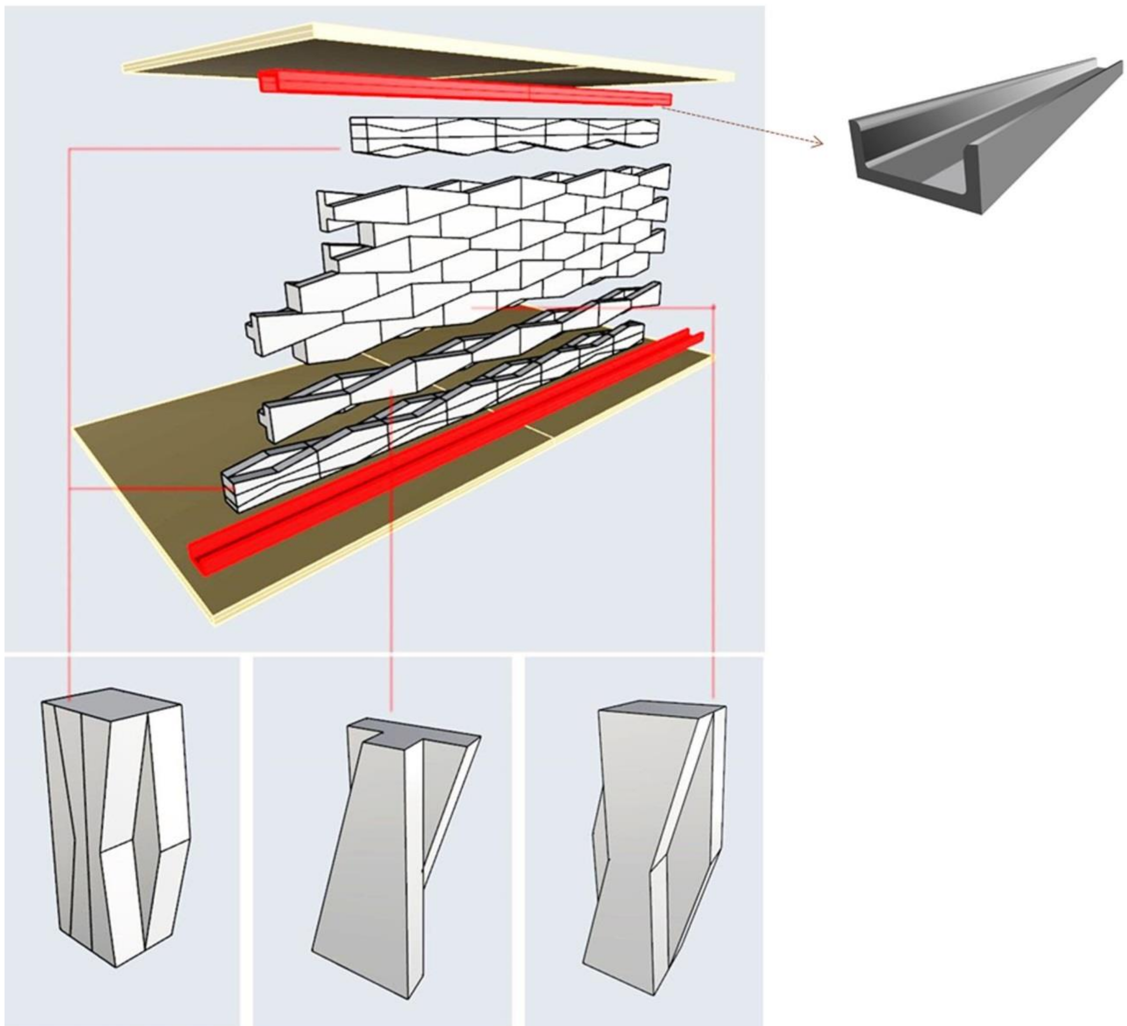


Figure **5-2**: Assembly of the interlocking blocks into a straight wall

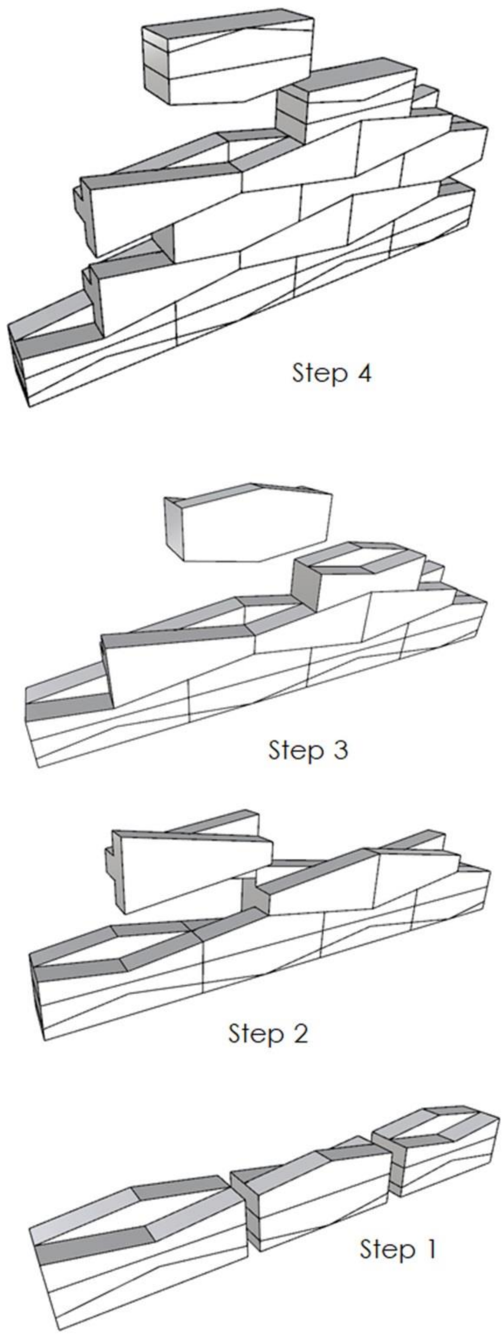


Figure **5-3**: Straight wall assembly steps

Figure 5-2 and figure 5-3 show how to assemble the proposed interlocking blocks to construct a straight wall as well as how to connect this wall to the floor and roof. Three types of blocks can be used to make straight walls: a block with a flat bottom or top, which can be used both as a base block (floor to wall connection) and as an end block (wall to roof connection), and two types of middle blocks. The printing direction of these blocks is also shown. The top and bottom of the wall is framed by a steel profile with an inverted C-shaped section (red color), which is connected to the roof or the floor.

L-connection Assembly

Figure 5-4 shows how to assemble the interlocking blocks to construct an L-connection between two walls. Three blocks are used for this purpose and they were generated by modifying the straight wall blocks. Two of them were generated by adding half of a similar block side-by side with a full block and the third one was modified by adding two halves of the same block to create a corner. This figure also shows the printing orientations used to make these blocks without the need for supports.

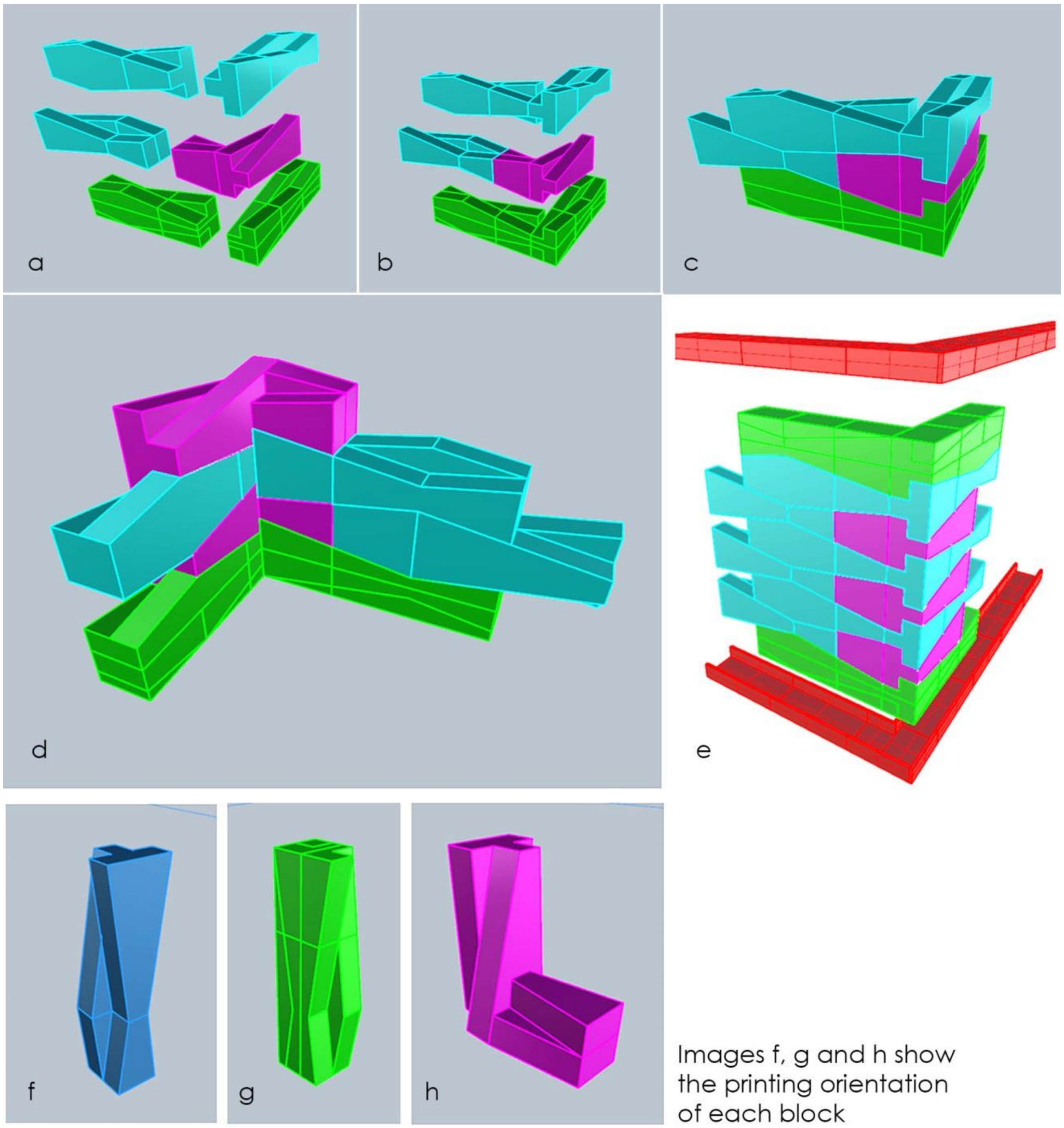


Figure **5-4**: L-connection assembly

T-connection Assembly

Figure 5-5 shows how to assemble the blocks to construct a T-connection. It can be described as a combination of straight wall assembly and an L-connection assembly. The orange colored block is used to connect the two walls and it is one of the three blocks used to create a straight wall. The printing direction of this block is also shown in the figure.

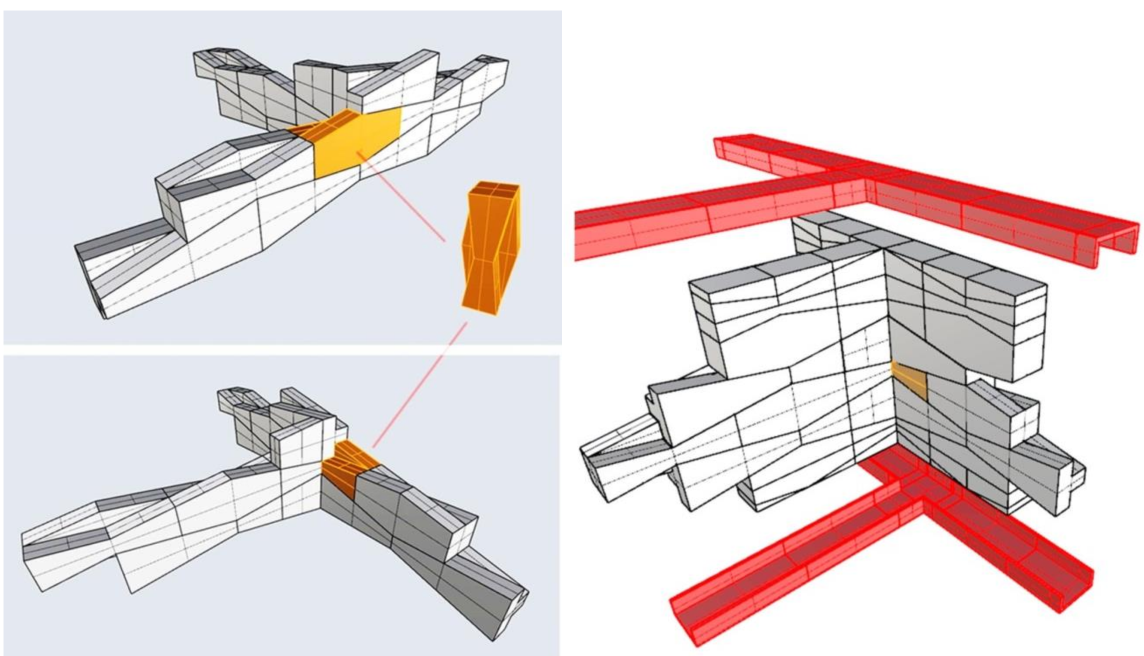


Figure **5-5**: T-connection assembly

Opening Creation

Figure 5-6 shows how to create an opening (door or window) using the interlocking blocks. It is similar to the straight wall assembly with some modifications. Here, the top end block is used as window sill and the base block is used at the top of the window as lintel. On the sides of the window, one of the blocks designed for the L-connection (the blue colored one) can be used to have a clean straight edge. For the lintel, a steel c-shaped profile is used similar to the one that was used for the floor to wall connection. This lintel is screwed to the bottom side of the blocks. This solution is for typical window settings. However, a perforated window block can also be designed and assembled as an integral part of the system.

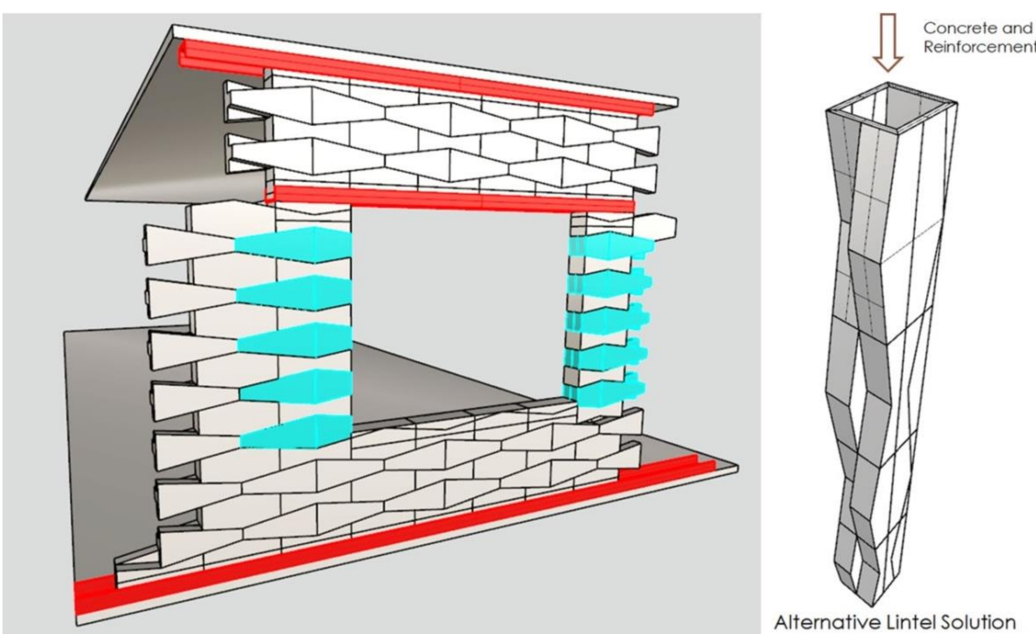


Figure **5-6**: Opening creation

Customization for Block Surface

Figure 5-8 and Figure 5-9 show two examples of blocks with customized textured surfaces. For this purpose, two different programs were created using Rhino and Grasshopper. These programs encode parametric models that can be manipulated to create customized textured surfaces by changing parameter values. The number of uniquely designed blocks that can be obtained in this way is potentially very large.

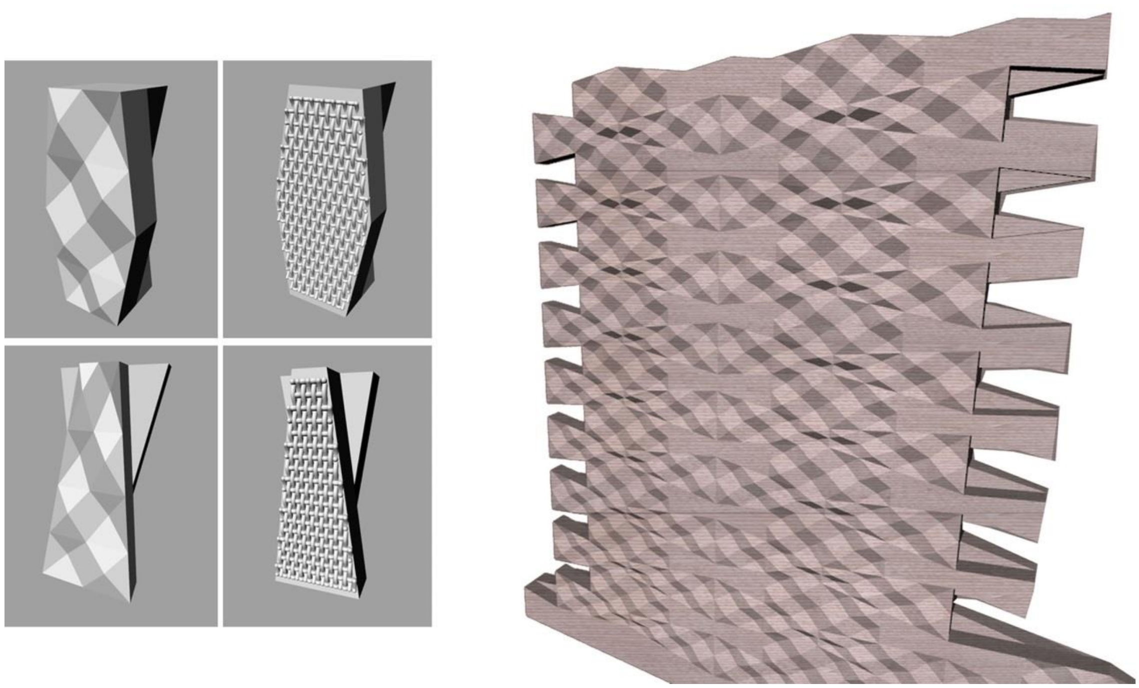


Figure **5-7**: Examples of blocks with customized surfaces and an example of a wall obtained by combining one of the blocks

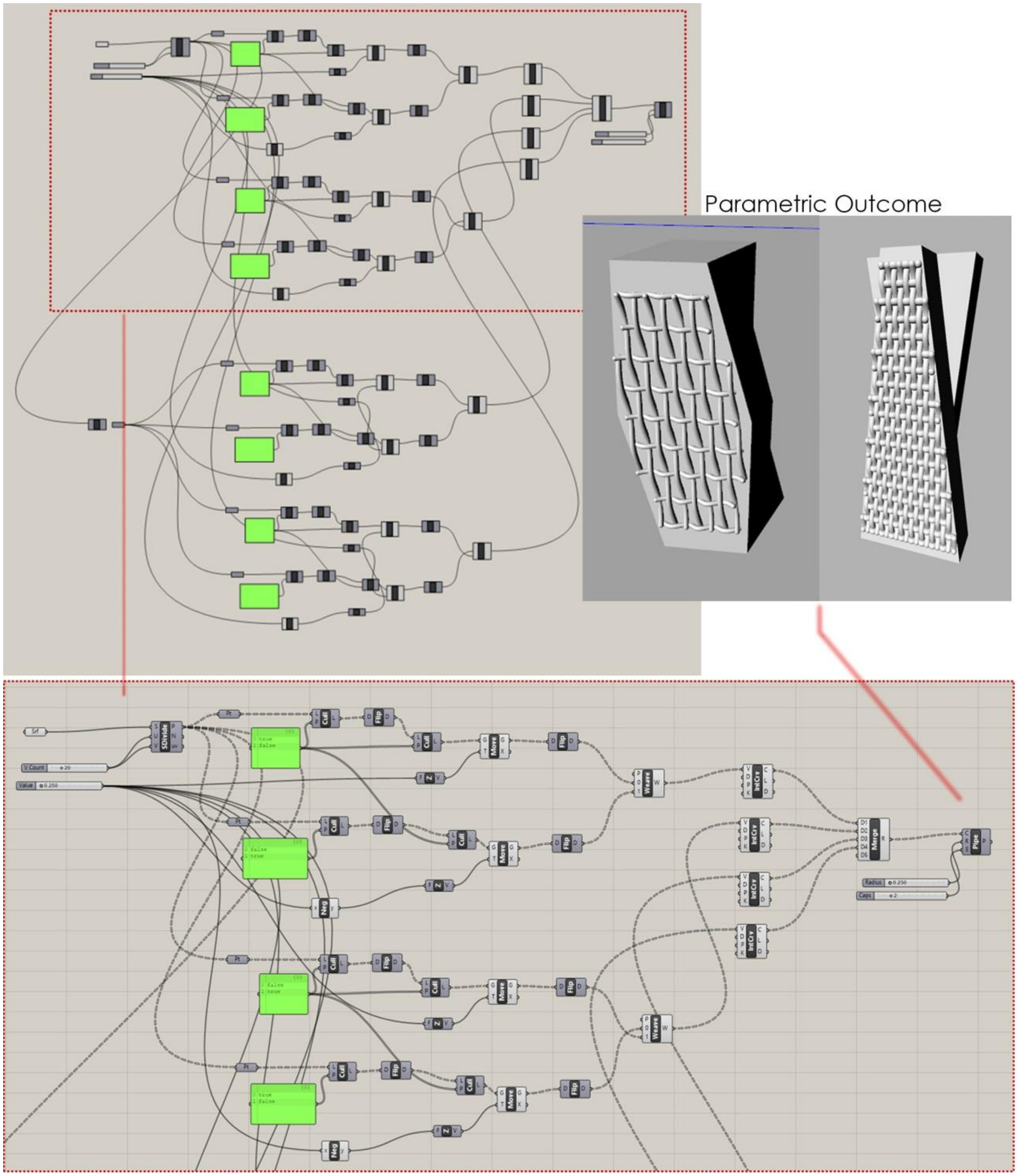


Figure **5-8**: Parametric model 1 for customizing block surfaces and two parametric variations

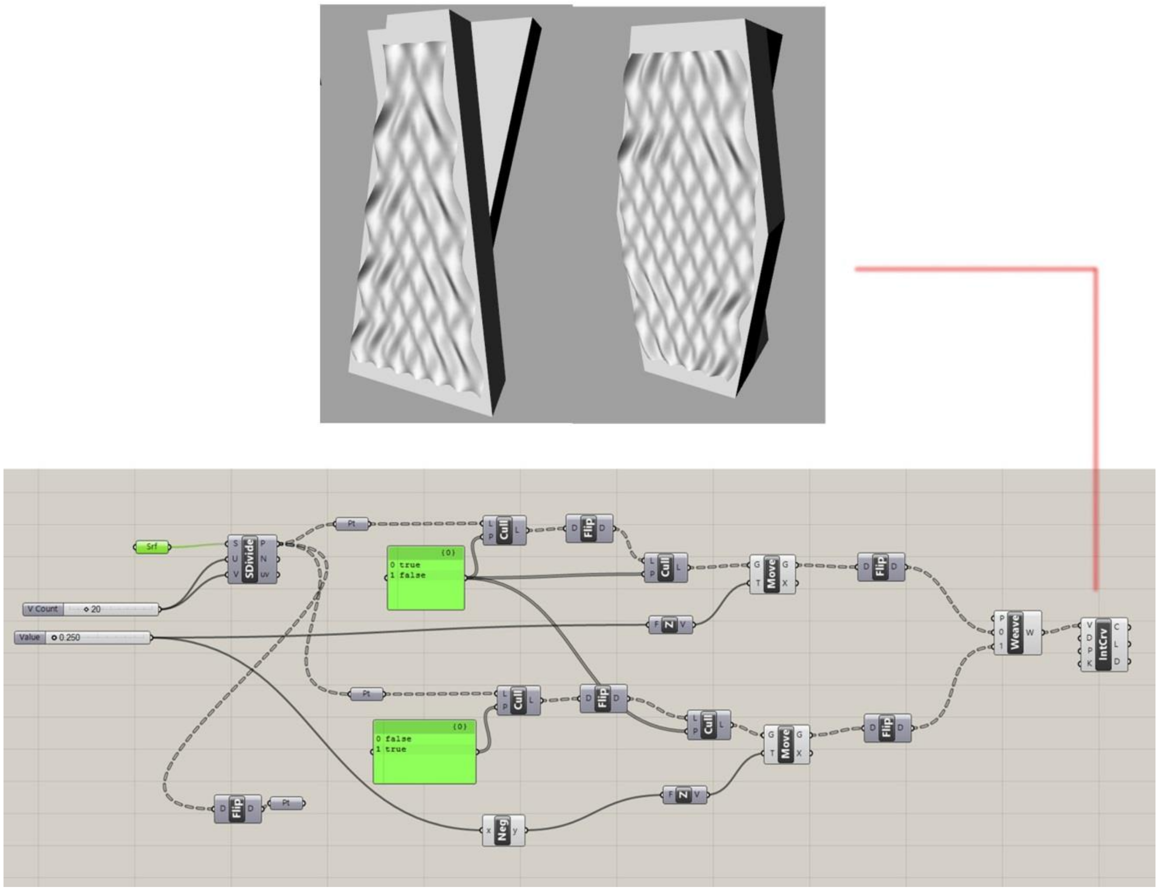


Figure **5-9**: Parametric model 2 for customizing block surfaces and possible parametric outcomes

Customizing Wall Surfaces

Figure 5-10 shows the first step in the design of a customized wall with interlocking blocks. A curved surface is used as an example. The program developed for this purposes was created using Rhino and Grasshopper. It encodes a parametric model for dividing a curved wall surface into a desired number of shapes, which can be used as a base geometry for interlocking component design. Then interlocking blocks can be designed by following the rules presented in Figure 5-1.

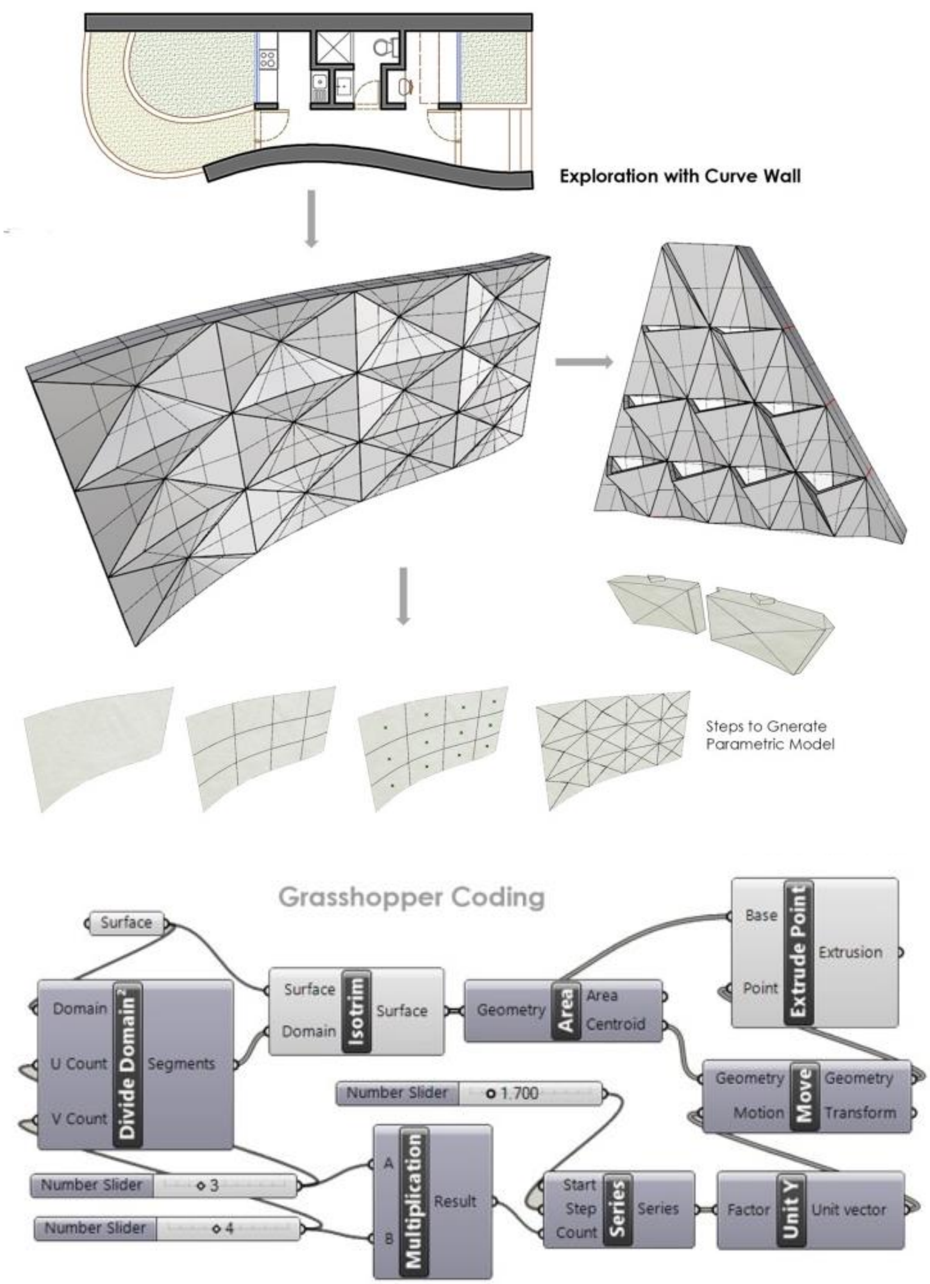


Figure **5-10**: Parametric model developed to divide a wall surface into interlocking blocks

Customizing Assemblies

Figure 5-11 shows how to assemble the different types of blocks proposed above to construct a house. The figure also shows how the blocks were designed for a particular case, namely, a tiny house with an integrated garden. In addition to blocks for building "typical" walls, several other interlocking blocks were designed in this case, including blocks for exterior walls with a vertical garden, and interior walls with shelves for storage. Figure 5-12 shows the plan of the proposed tiny house, as well as the top view and an exterior axonometric view.

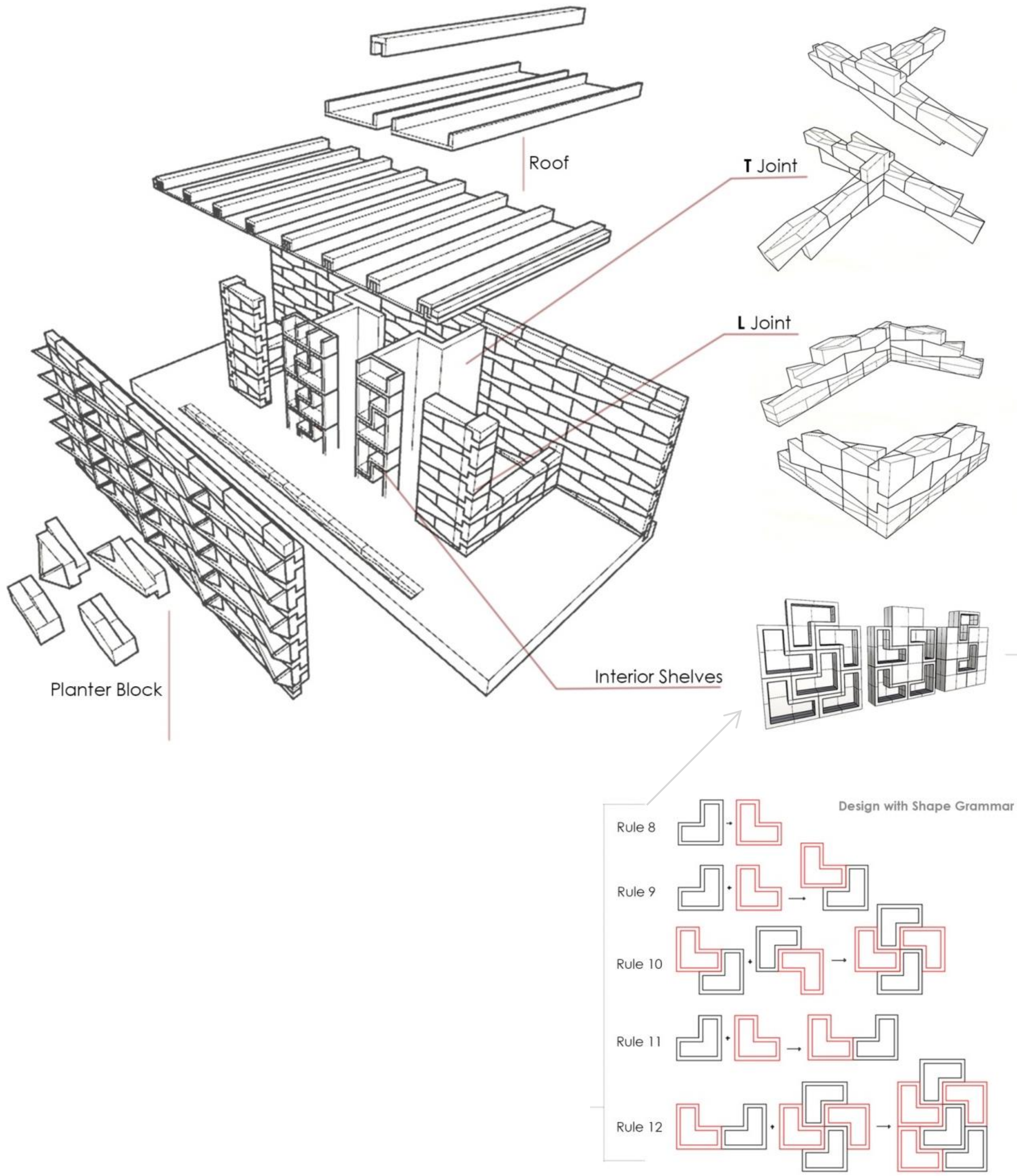


Figure **5-11**: Assembly of various interlocking construction components to construct a house

Figure **5-12**: Final outlook of the assembled house

In summary, the process just described shows how to create a system of customized interlocking blocks for generating customized houses.

Chapter 6

Conclusion and Next Steps

Research Outcomes

The outcomes of this research are fourfold: (1) differently shaped 3D printed interlocking construction components for constructing walls with different types of connections; (2) fine-tuned settings for 3D printing in clay; (3) a set of guidelines for designing and making interlocking construction components and for assembling them to construct a house; and (4) the design of a tiny house as a proof-of-concept of the proposed system of interlocking blocks.

Research Limitations

The proposed system of interlocking blocks presents two main limitations. The first is connected to structural stability due to loose connections and the second to permeability of the joints for the same reason. These limitations will constrain the usage of the system in terms of location and climatic conditions. For instance, the system is not suitable for seismic prone areas and cold climatic zones. However, it is suitable for hot dry and warm humid climatic zones, or as temporary shelters, or pavilions in other areas. However, the author believes that it would be possible to overcome some of these current limitations through further research.

Possible Future Research

This research opens the possibility of using 3D printed clay blocks in the construction industry. The study suggests that it is possible to 3D print building blocks using a low cost and open source customized 3D clay printer. Several future research steps can be taken to confirm this possibility. The most important ones concern structural stability, impermeability of joints, and the development of components for floor and roof systems. These future research steps are further discussed below

Structural stability

There are several possible ways to improve the structural stability of the proposed blocks. The width of the blocks can be increased to make walls more stable. The infill density can be raised to make it stronger and heavier and thus more stable too. The geometry can be improved to increase the structural stability of the interlocking system. All these options need to be tested to determine which option or combination of multiple options has the better performance.

Impermeable joint development

This can be done by introducing a second material. This material could be 3D printed, or added manually after the structure is assembled. Mastic sealant, for instance, could be used in this regard. However, other materials that offer a cheaper solution to this problem can also be explored. Unfired clay could be such a material. Mixing fine aggregates with clay is another option. To determine the suitability of such materials, one would have to take into account two criteria: how effective they are to prevent water to permeate the joints and how effective it is to remove them for reusing the blocks.

Construction components for floor and roof system

By nature clay is a brittle element. However, it is possible to make it stronger by mixing different types aggregates. Material exploration can be done to find out the strongest combinations. Then these solutions can be used for constructing floor and roof blocks. It is also possible to explore further the geometry of the blocks and introduce RE-bar and grout filling to improve their tensile and compressive strength capacity.

Conclusion

This research presents an initial exploration of a novel construction technology that combines three different aspects connected to design, making, and materials– interlocking blocks, low cost customizable additive manufacturing, and clay as an available and cheap building material. The easy deconstruction and reusability of these interlocking blocks will reduce deconstruction debris significantly. Therefore, successful implementation of this research at practical construction fields would be beneficial for both the construction industry and the environment.

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