Robotic stacking: structurally informed free-form timber structure system using standard and non-standard components

by

Zahra Falamarzi

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis is based on the hypothesis that the synchronization of digital design and robotic fabrication can result in new architectural possibilities. The research investigates differentiation and variability in the design of a structurally informed timber structure. This structure takes advantage of additive stacking through the robotic assembly of generic building elements. The aim of the project is to establish a closer link between robotic design research and contemporary building practice. This aim is achieved by developing an integrative approach to both structure and aesthetic potential through an optimized hybrid system using both standard and non-standard (easily manipulated during fabrication) components.

The idea is to create complex geometries and differentiation while benefiting from the concepts of automation and repeatability. The research considers several precedents, such as works by Gramazio and Kohler's research group at ETH Zurich. These projects were successful in using the unique capacity of industrial robots for precise positioning to control a large number of elements. Put simply, the industrial robot was employed as a means of design exploration rather than as a means of productivity. The robot was used where its digital controls became vital for applying the design, which could be considered the main purpose of robotic fabrication in architecture.

In this thesis, a construction method is developed for producing unique, complex geometrical forms of architectural elements, such as wall, roof, etc. Real-world parameters (materiality, construction, economy, and environmental concerns) are considered as important criteria driving the design in order to address common building practices. Essential parameters and limitations, extracted from a study of material choices, fabrication methods, and building-component specifications and requirements, shaped a set of rules that formed the hybrid structural design system of innovative "T" configuration modules.

The robotic-based assembly process, its corresponding design criteria, and the proposed system are examined through two physical experiments: the wall structure as a fundamental building element and the bench as a furniture structure, in order to validate the hypothesis that an articulated building component is achievable out of basic materials. The results present a new form of "digital craft" that could potentially impact conventional building practice. In summary, the proposed robotic-based production method, with its digital, parametric logic, provides possibilities for the structural system to be adopted at various scales and applied in different orientations, resulting in diverse architectural functions in a building-scale solution.

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1.INTRODUCTION

1.1 Digitally Controlled Fabrication Machines in Architecture

"Digital Fabrication could be defined as any manufacturing process controlled by a computer."[1]

As early as the 1950s, the first generation of computer-supported machines was developed. In the following fifty years, this technology, was transferred to numerous areas of industrial application.[2]

Since the beginning of the 1990s, the transition from traditional industrial production techniques to digital fabrication processes has also led to a significant shift in the production of architecture.[3] Stanley Davis introduced the concept "mass customization" in his 1987 book, *Future Perfect*, in which he redefined the manufacture of individual products using the methods of mass production. According to this redefinition, individual products can be made as economically as comparable mass-produced articles.[4]Now, non-standard manufacturing techniques have become familiar and common in architecture. While standardization was the driving force of technology in the industrial age, the manufacture of unique pieces plays a consequential role in the information age.[5]

The combination of digitally controlled fabrication machines with digital design tools has enabled the direct transformation of design information to the fabrication of architectural artefacts.[6] Seamless information flow enables the designer to gain greater control over the fabrication process, it also unites the processes of design and making.[7] As Fabio Gramazio emphasized in *Digital Materiality in Architecture*, control of digital fabrication is gained immediately by mapping the construction process onto a programmed process:

"From now on, we are no longer designing the form that will ultimately be produced, but the production process itself. Design and execution are no longer phases in a temporal sequence - design sketches do not need to be converted into the execution drawings anymore. The design incorporates the idea and knowledge of its production already at its moment of conception." [8]

There used to, usually, be a significant gap between the traditional medium of the architect – the amount and quality of information conveyed on a drawing – and the final physical outcome of builders.[9] Digital fabrication machines not only close this gap but also produce complex and unique components with a limited, or negligible increase in cost compared to standard components .[10] Instead of designing a static form, digital materiality leads us to design the relationships and sequences that inhabit architecture and that emerge as its physical manifestation.[11] Relationships and intentions are defined in the form of rules by using digital logics, and complex decision processes can be modeled by allocating different weight and priority to the influence that design-driven factors have on one another.[12] Therefore, instead of a static plan, a dynamic set of rules is available to the architect. Moreover, even fundamental changes can still be made very late in the process. As a result, the architect becomes an active author of an open design system, with control over the entire process from design to fabrication.[13] There are many other potential technical and economic benefits that digital fabrication has offer to architecture, including greater accuracy and precision, and improvements in speed, safety, and cost. However, there is still a lot for the construction industry to learn from other industries that are already heavily automated.[14]

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[1] Philip F. Yuan, Achim Menges, and Neil Leach, *Digital Fabrication* (Tongji University, 2018), 13.

[2] Fabio Gramazio, Matthias Kohler, and Jan Willmann, *The Robotic Touch: How Robots Change Architecture,* trans. Ralf Jaeger (Zurich, Switzerland : Park Books, 2014).

[3] Tobias Bonwetsch, "Robotically Assembled Brickwork: Manipulating assembly processes of discrete elements" (Dr. sc. diss., ETH Zurich, 2015).

[4] Stanley M. Davis, *Future Perfect* (Reading, MA: addison-Wesley, 1987).

[5] Gramazio, Kohler, and Willmann, *The robotic touch*.

[6] Bonwetsch, "Robotically Assembled Brickwork."

[7] Ibid.

[8] Fabio Gramazio, *Digital Materiality in Architecture* (Baden, Switzerland: Lars Muller Publishers, 2008), 8.

[9] Robin Evans, "Translations from Drawing to Building", *in Translations from Drawing to Building and Other Essays* (London: Architectural Association, 1997).

1.2 Robot as Digitally Controlled Fabrication Machine

While the term "robot" has a broad meaning that covers simple machines for automation to intelligent-acting autonomous devices, this thesis focuses on applying six-axis articulated-arm robots – generally referred to as industrial manipulators or industrial robots – to the form-making of architectural artefacts (Figure 1).[15] It should be noted that industrial robots are not intelligent devices but programmable machines.[16]

Figure 1. Examples of six-axis, articulated-arm robot.

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[10] Bonwetsch, "Robotically assembled brickwork."

[11] Gramazio, Kohler, and Willmann, *The Robotic Touch*.

[12] Ibid.

[13] Gramazio, *Digital Materiality in Architecture*.

[14] Yuan, Menges and Leach, *Digital Fabrication*.

[15] Bonwetsch, "Robotically Assembled Brickwork."

[16] Ibid.

Since industrial robots are programmable machines, definite similarities exist between them and computer numerical control (CNC) fabrication tools, such as routers, mills, or laser-cutters, which have been applied in the architectural realm in the last two decades.[17] According to Tobias Bonwetsch, what distinguishes industrial robots from common CNC machines, however, are the following characteristics: "1) their universal nature, 2) their suitability for different assembly tasks, and 3) the ability to work in a 1:1 constructive scale."[18] These features are described below.

1.2.1 Universal Nature

Industrial robots are defined as "automatically controlled, reprogrammable, multipurpose manipulator[s], programmable in three or more axes, for use in industrial automation applications."[19] To simplify, an industrial robot is a machine that can perform movements along multiple axis, and execute different manufacturing tasks. Industrial robots can be adapted to perform a broad range of material manipulations; therefore, they can be understood as universal fabrication machines.[20] They are similar to computers in their general nature, with the difference that industrial robots perform operations on physical entities, while computers perform operations on information.[21] It should be noted that industrial robots' inherent multi-functionality counts as their biggest advantage when compared to other conventional machines. They can be equipped with basically any tool and, similar to a human hand, a robotic arm can apply its tools from all directions and orientations.[22] End-effectors, as well as peripheral devices such as external tools, additional external axes, or sensors can enable the robot to perform specific material manipulations with high precision, thus comprising an industrial robot system.[23] The end-effector tools can be generic (robot gripper) or they can be highly specific and unique for a particular fabrication process. They can be designed not only to perform a physical material manipulation, but also to gather information, for example by examining, scanning, or measuring. As such, an industrial robot can be named as a generic tool that integrates a multitude of different fabrication machines in one (Figure 2).[24]

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[17] Ibid.
[18] Ibid. 4.
[19] Achim Menges, Tobias Schwinn, and Oliver David Krieg, eds., *Advancing Wood Architecture: A Computational Approach* (London: Routledge, 2016).
[20] Bonwetsch, "Robotically Assembled Brickwork."
[21] Ibid.
[22] Yuan, Menges, and Leach, *Digital Fabrication*.
[23] Bonwetsch, "Robotically Assembled Brickwork."
[24] Ibid.

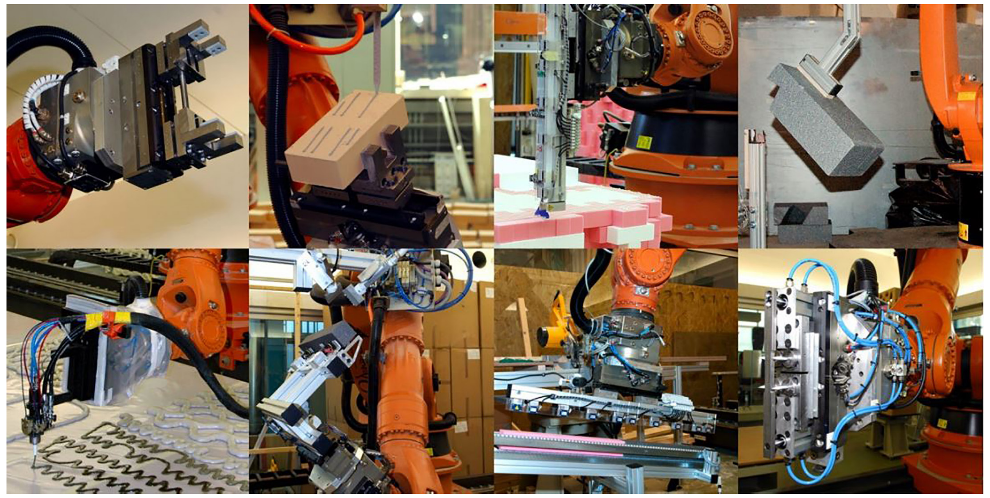

Figure 2. Different custom-designed end-effectors that can be attached to the robot arm to perform a variety of different manipulations.

1.2.2 Suitability for Different Assembly Tasks

The kinematics of the robotic arm make it highly suitable for assembly tasks, which distinguishes it from CNC machines.[25] While CNC machines are geared towards the production of components predominantly through cutting or deformation processes, these components still need to be assembled.[26] In fact, construction can generally be defined as the assembly of different parts and materials.[27] Therefore, it can be argued that, industrial robots are specifically well suited for construction work among the family of digitally controllable machines.[28]

1.2.3 Ability to Work at a 1:1 Constructive Scale

The industrial robot's unique custom-configuration capabilities offer the opportunity for fabrication processes to take place outside the given framework of common CNC machinery.[29]

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[25] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[26] Bonwetsch, "Robotically Assembled Brickwork."
[27] Ibid.
[28] Ibid.
[29] Ibid.

The robot can carry out a nearly unlimited number of physical operations freely in space through programming. While there is a scale limitation in other digitally controlled fabrication machines, industrial robots can be mounted on moving machines, expanding their working area and freely moving in space.[30] This radical step in the spatial relationship between machine and building is an important turning point for the use of digital fabrication machines in architecture and construction. The ability to work at the actual scale of construction is another central ability of the industrial robot.[31]

1.3 New Possible Spectrum of Material and Fabrication by Robots in Architecture

Interest in the application of robotic systems in the fabrication of architectural pieces and construction work has increased in the last decade. However, the focus of this interest is shifting from automating the building process and increasing productivity to a design-oriented approach.[32] The concentration has been on the inherent variability of the robotic system, and how this can engage with the architectural design process. Put simply, architects and designers are using robotic systems as a means of design exploration rather than automation of construction work.[33] By recognizing the robot as a typical, generic production tool, its true potential is revealed to address architecture's particular production circumstances, rather than fitting architecture to the particularities of the tool.[34] According to Gramazio, "the robot connects the digital reality of the computer with the material reality of built architecture. The simple insight that architecture is largely built through the addition of parts or the aggregation of materials allows us to advance digital fabrication. As we accumulate material precisely at the point where they are needed, we can weave form and function directly into building components, and are not limited to the design of their surfaces. The industrial robot enables us to implement this additive principal on an architectural sale." [35]

A pioneer in the field of robotics in architecture, Gramazio compares the potential of robots in architecture and construction to that of computers; similar to personal computers, which have not been optimized for one single task but are suitable for a range of applications, robots can be applied to different tasks and in different capacities for physical manipulation and processing.[36] Gramazio adds that, "By defining the robot's hand _ also referred to as the 'end effector'_ and determining its movement, we teach the robot a desired type of construction. We teach it to register its surroundings through sensors, and to affect the environment through the robot hand. The robot thus connects the world of immaterial logic to that of material construction in the most direct way."[37]

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[30] Ibid.
[31] Ibid.
[32] Ibid.
[33] Ibid.
[34] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[35] Gramazio, *Digital Materiality in Architecture*. 8-9.
[36] Ibid.
[37] Ibid. 9.

In fact, conceptual links between the spatial characteristics of design and the robot's spatial-constructive materialization possibilities can expand architectural design concepts.[38] By reintroducing the robot as a design exploration tool rather than a production machine, and by focusing on its conceptual openness and versatility, many innovative possibilities have arisen in recent years along the widest possible spectrum of material articulation.[39] Simply put, from the viewpoint of integrating design and fabrication, architects tend to adopt a new approach to the new paradigm of architectural form-finding process.[40] In other words, there has been a shift from form-driven to performance-driven design. By linking the design concept to the process of robotic fabrication, the parametric aspect of architecture can not only be defined geometrically for performance-based purposes, but can also be effectively actualized through robotic fabrication.[41]

Within this new design methodology (integration of fabrication through the design), the study of material systems plays an important new role. The performance of materials and their possible manufacturing techniques is taken into account from the very first step of the design process.[42] Material opportunities in robotic fabrication can range from discrete building components such as brick, timber, and metal to those of granular and malleable materials such as concrete, sand, foam, and clay. Robots can generate material through direct external manipulation (e.g. cutting timber slats to length) or process the material to specific properties (e.g. expansion of polyurethane foam). A variety of different custom-designed end-effectors can be attached to the same robotic arm to perform a variety of different processes.[43] They are able to transfer computational design data directly to fully automated construction of non-standard and complex-geometry structures. This precise strategy for material manipulation can be categorized into three main types: subtractive, additive, and positioning, or a combination thereof.

1.3.1 Subtractive Processes

Industrial robots can be applied to mimic existing CNC machines. As Bonwetsch emphasizes, "in fact, a great number of projects in architecture apply robotic fabrication in that way."[44] Examples are the ICD/ITKE Research Pavilion (Institute for Computational Design, University of Stuttgart), Germany, 2011 (Figure 3), and the Robotic Timber Fabrication by David Correa and Oliver D. Krieg at the University of British Columbia, Canada, 2017 (Figure 4), where an industrial robot was applied as a milling tool.

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[38] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[39] Ibid.
[40] Yuan, Menges, and Leach, *Digital Fabrication*.
[41] Ibid.
[42] Ibid.
[43] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[44] Bonwetsch, "Robotically Assembled Brickwork."

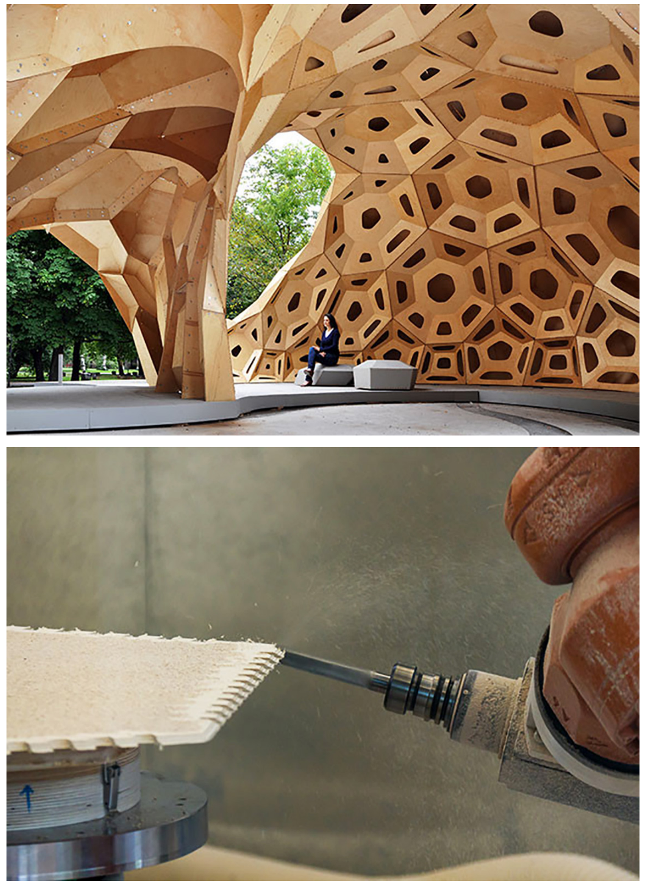

Figure 3. ICD/ITKE Research Pavilion, Germany, 2011.

As Menges mentions in *Advancing Wood Architecture*, a successful example of transferring long-established techniques into the contemporary realm of computational design and construction are robotically fabricated finger joints.[45] This area has been the subject of research at the ICD for many years. The robotic fabrication process enables joining of elements with a variety of thicknesses at a range of different angles.[46] The ICD/ITKE Research Pavilion exemplifies the use of plates with robotically fabricated finger joints in a structure at an architectural scale. A set of performative morphological principles was identified by extracting and analyzing finger joints parameters and rules; later, these constraints were transformed into algorithmic design rules.[47] The final light-weight structure shows both the architectural and the structural potential of a system that consists of 6.5 mm-thin plywood sheets that are connected by more than 100,000 different finger joints.[48] The precise fabrication of this many different joints is only possible through robotic fabrication, rather than previous conventional construction methods.

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[45] Menges, Schwinn, and Krieg, *Advancing Wood Architecture*.
[46] Ibid.
[47] Ibid.
[48] Ibid.

Figure 4. Robotic Timber Fabrication, University of British Columbia, 2017.

The Landesgartenschau Exhibition Hall (Figure 5), by ICD/ITKE, 2014, went beyond what was achieved in the 2011 Research Pavilion. This project aimed to expand the scope of research from fabrication and assembly to integrate a wider range of building requirements for a permanent structure. This permanent building structure consists of three main layers. A new-generation scheme for segmented shell structures is used to form the building's architectural character.[49] The lightweight, timber-plate structure was robotically fabricated from locally sourced beech plywood and formed the primary structure of the building. The insulation, waterproofing layer, and final cladding sheets, which were added to the main frame structure, form a fully enclosed building.[50] Considering the timber-plate system in building practice, the joints are designed with 0.5-mm tolerances in order to prevent structural failure from possible accumulated error of fabrication inaccuracies, as well as possible deformation of the plates between fabrication and assembly due to changes in environmen-

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[49] Ibid.
[50] Ibid.

tal conditions.[51] The load-bearing capacity of the overall shell structure is fundamentally reliant on the connections between plates. However, the structural calculation is not the only item that needs to be considered when determining plate thickness and joint design. Related building regulations and fire safety rules play important roles.[52]

Figure 5. The Landesgartenschau Exhibition Hall, ICD/ITKE, 2014.

In summary, these projects used the robot in a very similar manner to the CNC machine.

1.3.2 Additive Processes

The process of additive manufacturing with a robot enables a wider extent of capacities compared to existing 3D printers. The Mesh Mould is an example of this process. This research project was completed at the Singapore-ETH Centre, Future Cities Laboratory, in 2012 (Figure 6).

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[51] Ibid.
[52] Ibid.

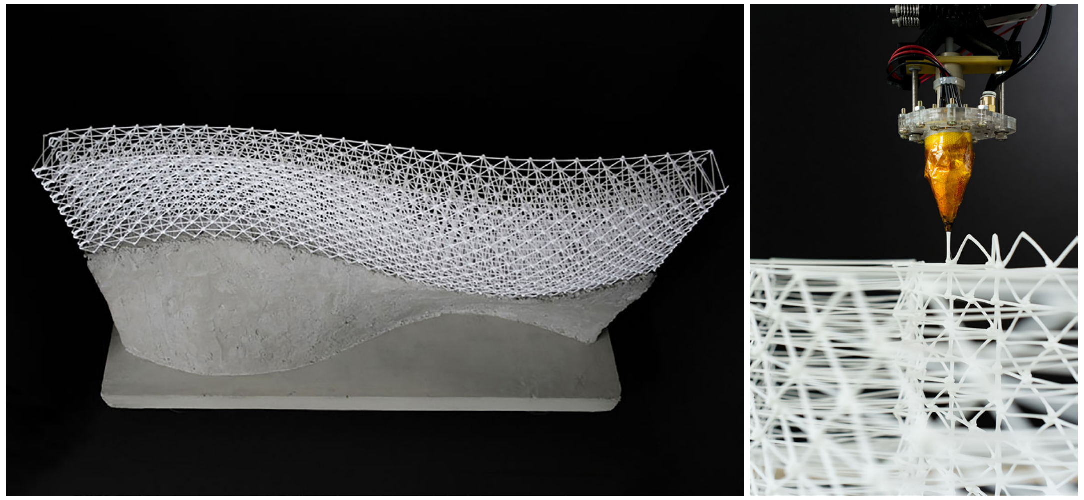

Figure 6. The Mesh Mould, Singapore-ETH Centre, 2012.

To make Mesh Mould, an industrial robot extrudes filament freely in space, producing a digitally controlled, three-dimensional mesh structure. The final mesh structure adopts an optimized density with regard to structural performance. The conceptual change from layer-based deposition to spatial extrusion allows for a significant reduction of both time and weight. This extremely light mesh structure is very suitable for the construction of complex free-form geometries out of concrete.[53]

Another example in this area is the Robotic Multi-Dimensional Printing Based on Structural Performance project, conducted at the Digital Design Research Centre, Tongji University (Figure 7). A six-axis robot is programmed using a customized printing end-effector to build free-standing geometries in space. It should be noted that the printing tools are designed with additional extruders and nozzles of various dimensions to adapt to different materials according to design requirements.[54] Philip F. Yuan summarized that a flexible and adaptive additive manufacturing methodology is thus established. This potential for a high degree of spatial and structural complexity associated with combining 3D printing and robot technology, opens new possibilities in architectural structures.[55]

Cloud Village, by Philip F. Yuan, was a 3D-printed outdoor installation that formed the Chinese pavilion at the 16th International Architecture Exhibition (Figure 8). It is an example of 3D printing by robots being used at a larger architectural scale. The pavilion was made of

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[53] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[54] Dagmar Reinhardt, Rob Saunders, and Jane Burry, eds., *Robotic Fabrication in Architecture, Art and Design 2016* (Cham: Springer, 2016).
[55] Ibid. 92-105.

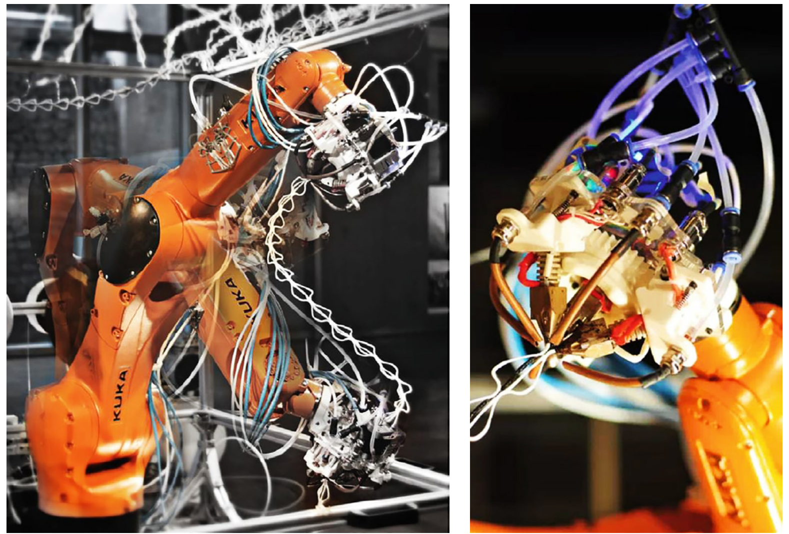

Figure 7. Robotic Multi-Dimensional Printing Based on Structural Performance.

components prefabricated in the shop and assembled on site. The structure was made with five different densities according to different structural performance requirements, forming a continuous geometry knitted by a robot arm with recycled plastic.[56] The structure could be considered as a temporary space where people can sit, think, and relax, creating an interaction between the individual and the community. The project demonstrates China's architectural heritage and traditional building techniques combined with technological and conceptual innovation in contemporary architecture.[57]

Figure 8. Cloud Village, Chinese Pavilion at the 16th Venice Biennale 2018.

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[56] Joanna Wong, "Chinese Pavilion Opens with Robot-Printed ' Cloud Village' at 2018 Venice Biennale," *ArchDaily*, accessed January 29, 2019, https://www.archdaily.com/894986/chinese-pavilion-opens-with-robot-printed-cloud-village-at-2018-venice-biennale.
[57] Riccardo Bianchini, "Building a Future Countryside – The China Pavilion | 16th Venice Biennale 2018," *Inexhibit*, August 13, 2018, https://www.inexhibit.com/case-studies/building-future-countryside-china-pavilion-16th-venice-biennale-2018/.

1.3.3 Positioning

In the building industry, construction is generally defined as the assembly of different parts and materials in the correct relative position.[58] As mentioned before, what makes robots different from other digitally controlled fabrication machines is their flexibility to undertake different assembly tasks and, in particular, the ability to work at a 1:1 constructive scale. A project that illustrates this potential is the Gantenbein Vineyard Façade (Figure 9).

Figure 9. Gantenbein Vineyard Facade, Switzerland, 2006.

This project points out how a high level of positioning precision can be addressed through digital design implemented by a robot, leading to innovative architectural qualities.[59] It is associated with the transition from repetitive manual or industrial labour to a digitally differentiated robotic fabrication process.[60] Due to the individual position of each

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[58] Bonwetsch, "Robotically Assembled Brickwork."
[59] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[60] Ibid.

brick, and its complexity of offsets and angles, this project could not be built by hand. While such complex materialization processes would be very difficult to achieve through traditional design methods, they become manageable and freely formable through computer programming. This millimeter-exact alignment and differentiation made little sense before the robot became available in architecture.[61]

Figure 10. The Stacked Pavilion, Switzerland, 2009.

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[61] Ibid.

Despite significant progress in timber prefabrication using widely available computer numerical control (CNC) systems, the timber construction sector is still highly dependent on manual assembly tasks. Fully automated construction is possible by robot arm using the robot's ability to transfer computational design data to real-world assembly operations. In fact, it is possible to unify the fabrication process for a whole structural system at the scale of a building (the digital integration of all additional processing of each element and the assembly of whole).[62] The Stacked Pavilion (Figure 10), Wettswill am Albis, Switzerland, 2009, a temporary spatial structure, represents a further stage of development in this regard. More than 5600 timber slats are cut to custom lengths and placed by robot in the space according to an algorithmic design.[63]

Figure 11. The Sequential Structure, Switzerland, 2010.

The Sequential Structure (Figure 11), a teaching project by ETH Zurich, Switzerland, 2010, is another experiment that has been expanded from an additive, layer-based system to a system of freely aggregating in space.

The Sequential Roof (Figure 12) project by ETH Zurich, Switzerland, 2010, is one of the full-scale industrial implementations of this concept.

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[62] Menges, Schwinn, and Krieg, *Advancing Wood Architecture*.
[63] Gramazio, Kohler, and Willmann, *The Robotic Touch*.

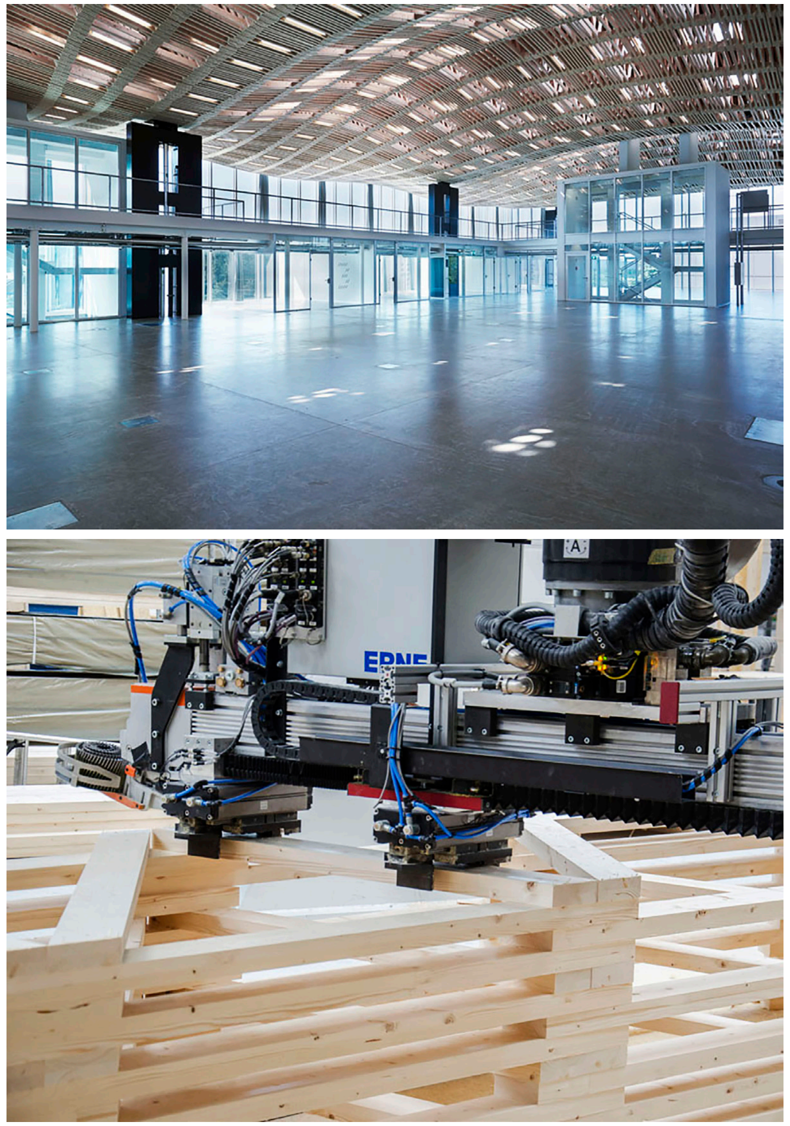

Figure 12. The Sequential Roof, Switzerland, 2010.

In conclusion, although assembly-driven design through robotic fabrication represents an evolution in the construction industry, building-scale robotic timber construction is still in its infancy. Challenges surrounding economy of scale, robotic expertise, and design expertise are yet to be addressed.

1.4 Thesis Structure

This research develops a robotic-based production method for building a complex-geometry wall using the unique capacity of robots to perform assembly tasks. The double-curvature wall is designed through an additive fabrication method. Possible variability and differentiation through scripting design and assembly of generic standard components are explored in the design approach.

The thesis is structured in six chapters. Following an overall introduction on the potential of digitally controlled fabrication machines and new possibilities of robotic fabrication in architecture, Chapter 2 reviews the application of robotics in the construction industry so far, with a history of accomplishments and failures in this regard. The new phase of interest in using robots in architecture, “design-through-fabrication-process,” and the concept of digital materiality are discussed.

Chapter 3 presents the particular possibilities of robots’ suitability in assembly, how architectural capabilities can be addressed by digital design through robotic assembly, and how architecture becomes increasingly rich and diversified through the concise materialisation of robotic assembly of an algorithmic design. Two examples, the Sequential Wall and Structural Oscillations, are analyzed and explored in depth with regards to different aspects of their design and fabrication systems.

Chapter 4 covers the thesis research design. Both the design and the process of making are seen as integral parts that correspondingly informed one another. Design-driven criteria and fabrication parameters are extracted and frame the methodology of this research project. These parameters later form a set of algorithmic rules in computational design software for both the design system and fabrication process. Moreover, the material and computational system are explained in more detail, illustrating the capabilities of the design system in different functions and at diverse scales. Finally, the fabrication tools and process are explained in detail, describing challenges and limitations throughout the process.

Chapter 5 reviews the fabrication processes of two physical prototypes conducted at the digital lab of the Waterloo School of Architecture. Each prototype investigates the unique design space that the presented stacked timber structure system enables. In the first experiment, the robotic assembly of standard components is applied to an architectural element, a wall. For the second experiment, robotic assembly of non-standard (minimal customization of standard) components is applied to a furniture element, a bench.

Chapter 6 presents the future outlook of this research. Investigations of scale, architectural spatial quality and structure are presented and discussed in relation to conceptual and technical challenges. Moreover, further potential research that could be conducted as part of further development stages is discussed.

2. CONTEXT : ROBOTICS IN ARCHITECTURE

2.1 The Advent of the Universal Fabrication Machine

The first patent for an industrial robot was granted to George Devol in 1954.[64] The invention was termed "universal automation," and made a direct analogy with computers.[65] In 1961, the first industrial robot, "Unimate," was developed by Joseph Engelberger for use by General Motors.[66]

Articulated-arm robots as we know them today emerged in the 1970s and were designed by Victor Scheinman.[67] In 1973, the IRB-6 robot was presented by ASEA (Allmänna Svenska Elektriska Aktiebolaget, a Swedish industrial company).[68] The IRB-6 followed an anthropomorphic design and its movements followed those of a human arm. FAMULUS by KUKA (Keller und Knappich Augsburg, a German manufacturer of industrial robots), with six electromechanical driven axes, was produced the same year.[69]

In the 1980s, the industrial robot industry quickly became universal and manufacturing was automated at a large scale.[70] Although there have been significant advances in the field of industrial robotics from the 1970s to today, the basic concept of the articulated-arm robot has not changed dramatically since then, and only improvements in speed, accuracy, and weight have been made to the robot arm.[71] However, performing repetitive tasks in a controlled manufacturing environment, which can be pre-programmed, has remained the existing use of industrial robots and their primary focus.[72] Since the integration and programming of robotic systems is still a complex and time-consuming endeavour, their application for small lot sizes or one-of-a-kind production remains limited.[73]

2.2 History of Robotics in Architecture and Construction

The first attempts to apply robotics to construction work can be traced back to the late 1970s[74]; however, a coherent history of robotics in architecture and construction has not yet been developed.[75] The historical overview presented in this chapter is thus necessary for the present thesis in order to embed precedent approaches, as well as contextualize contemporary efforts. This overview highlights only a selection of applied research projects that are clearly dedicated to applying industrial robots to construction processes, which are most relevance to the present work.[76] As Bonwetsch suggests, "It is important to note that the history of robotics in architecture and construction also features disruptions and does not at all follow a linear progression towards a predefined outcome. In fact, a successful implementation of robotics in the field of architecture and construction cannot yet be foretold."[77]

The application of industrial robots in the building industry was of interest as a means to increase productivity through automation.[78] Initial research into this topic started in 1978 in Japan. The International Symposium on Automation and Robotics (ISARC) has been held annually since 1984, giving a comprehensive overview of the research devoted to robotics in architecture and construction.[79] Interest in applying robotics to construction has grown ever since, and the International Association for Automation and Robotics in Construction (IAARC) was founded in 1990.[80] Civil infrastructure and housing are two main fields that were of interest to the construction industry in terms of robotic fabrication.[81]

David Gann states that competition between construction firms in Japan during 1980s and1990s was mainly technologically driven, as opposed to solely price based as in most other countries. Thereby, investment in research and development was double in proportion to construction output.[82] Restrictive worker policies in Japan resulted in a growing need to increase productivity in construction due to a lack of skilled labour. Therefore, interest in investing in robotics for construction was higher compared to other industrialized countries during the 1980s and 1990s.[83]

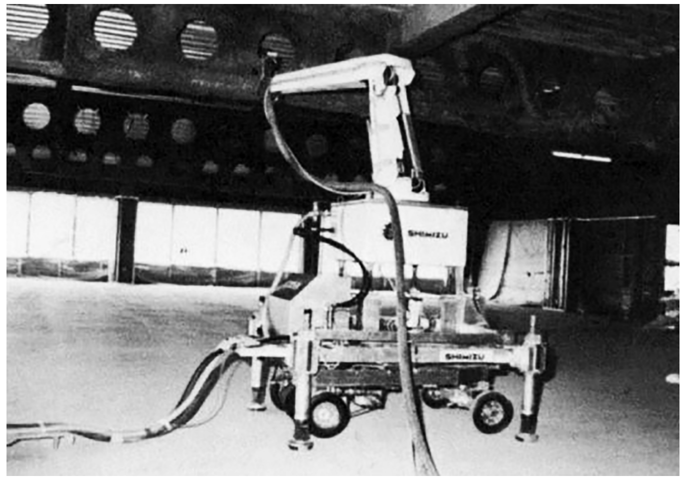

Figure 13. Shimizu Site Robot (SSR-1).

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[64] Bonwetsch, "Robotically Assembled Brickwork."
[65] Ibid.
[66] Ibid.
[67] Victor David Scheinman, "Design of a Computer Controlled Manipulator" (PhD diss., Stanford University, 1969).
[68] Bonwetsch, "Robotically Assembled Brickwork."
[69] Ibid.
[70] Ibid.
[71] Ibid.
[72] Ibid.
[73] Ibid.
[74] Yukio Hasegawa, "A New Wave of Construction Automation and Robotics in Japan," Waseda University, 2000.
[75] Bonwetsch, "Robotically Assembled Brickwork."
[76] Ibid.
[77] Ibid. 12-13.
[78] T. Bock and S. Langenberg, "Changing Building Sites:
Industrialisation and Automation of the Building Process," *Architectural Design* 84, no. 3 (2014): 88-99.
[79] Bonwetsch, "Robotically Assembled Brickwork."
[80] Ibid.
[81] Carlos Balaguer and Mohamed Abderrahim, "Trends in Robotics and Automation in Construction," in *Robotics and Automation in Construction,* ed. Carlos Balaguer and Mohamed Abderrahim (Location: InTech, 2008).
[82] David Gann, *Building innovation: Complex Constructs in a Changing World* (London: T. Telford, 2000).
[83] Tobias Bonwetsch, *Robotically assembled brickwork*.

In 1984, the Shimizu Construction Company – one of Japan's largest construction firms – applied a robot to construction for the first time. The Shimizu Site Robot-1 (SSR-1) (Figure 13) was applied to spray of fireproofing.[84] The test demonstrated the feasibility of applying a robot for on-site construction work and, at the same time, exposed certain obstacles to applying industrial robots to construction. For instance, the size and weight of the robot were too great for it to be transported in a lift and used on different floors, or moved through doorways. In addition, controlling the robot was complex and operators had to be thoroughly trained at a time when training costs were relatively high.[85] The SSR-1 was based on a commercial articulated-arm robot; on the other hand, development was also focused on custom robotic devices optimized to perform a single specific task. Examples of surface finishing of concrete slabs are Mark II, the SurfRobo, and the FLATKN (Figure 14).[86]

Figure 14. Concrete finishing robots: (left)SurfRobo by Takenaka Corporation; (middle) Mark II, also known as Kote-Kirg by Kajima Corporation; (right)FLATKN by Shimizu Corporation.

In addition to single-purpose robots, integrated construction automation systems were also developed in order to create a factory-like situation on the construction site.[87] In these types of systems, a temporarily covered working platform is assembled on the constructed floor of the structure. The working platform provides automated material handling systems for robots to perform diverse construction tasks.[88]

"Future Home"[89] and "Manu Build"[90] are examples of research that followed the European integrated approach towards robotics and automation in construction, which ran from 1998 to 2002 and from 2005 to 2009, respectively. The primary goals were improving productivity, quality, safety, and achieving a reduction in construction costs. These projects have not yet made a noticeable impression on the building industry, despite receiving considerable funding.[91]

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[84] Ibid.
[85] Roozbeh Kangari and Tetsuji Yoshida, "Prototype Robotics in Construction Industry," *Journal of Construction Engineering and Management* 115, no. 2 (1989); 284-301.
[86] Bonwetsch, "Robotically Assembled Brickwork."
[87] Ibid.
[88] Ibid.
[89] Ibid.
[90] T. Bock, "The Integrated Project ManuBuild of the EU" (paper presented at the 23rd International Symposium on Robotics in Construction (ISARC), Tokyo, Japan, 2006).
[91] Bonwetsch, "Robotically Assembled Brickwork."

Common to all of the above examples, the aim of applying robotics in construction was to achieve a high degree of automation in order to increase productivity and quality. These systems are highly dependent on standardization and prefabrication. The working platform constrains the vertical configuration of the building and thereby limits the freedom of architectural design. The rigidity of the system also had significant challenges in reacting to unforeseen conditions on construction sites.[92]

2.3 Limitations of the Earliest Robotic Approach in Construction

The first phase of robotics in construction reached its peak in the 1990s. Over 200 different prototypes of robotic solutions, including mechatronic devices ranging from entirely autonomous machines to tele-operated apparatuses, had been developed for the construction industry and tested on building sites.[93] Carlos Balaguer and Mohamed Abderrahim state that the main barrier for robotics and automation in construction was the "nature of the work environment," which is unstructured.[94]

Generally, the concepts applied to other manufacturing-based industries were directly transferred to the building industry.[95] Therefore, substantial differences in the product were ignored (e.g. an automobile versus a building). First of all, there is a difference in scale. While the entire workspace needed to assemble a vehicle can be reached by a set of four to six robots in a fixed position, this is not possible in building construction, since the workspace required to build a building is much larger. In consequence, the construction robots, which had to be more mobile, faced numerous additional challenges (e.g. issues of perception and orientation).[96] Secondly, there are significant fundamental differences between manufacturing and construction. One of the main differences and, perhaps, the most important one, is that the building industry is mainly project-based – each project is significantly different from its precedents. While several factors are involved, ranging from architects to contractors and suppliers, coordination remains an issue. Every building is designed for a specific function, on a certain site, and to meet a client's distinctive demands. Also, the building industry mainly consists of small- to medium-size enterprises (SME) that are unwilling to make large investments such as robotic equipment and expert training.[97]

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[92] Ibid.
[93] T. Yoshida, "A Short History of Construction Robots Research & Development in a Japanese Company" (paper presented at the 23rd International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan, 2006).
[94] Balaguer and Abderrahim, "Trends in Robotics and Automation in Construction."
[95] Bonwetsch, "Robotically Assembled Brickwork."
[96] Ibid.
[97] Ibid.

In summary, increasing productivity and achieving economic benefits were the main targets accomplished through the usage of automated machines. Saving labour, reducing costs, and obtaining quality control in production were the main aims. Highly specialized robotic systems that cannot react to different design situations are too expensive for most companies in the construction industry.[98] Moreover, a common approach to address the inflexibility of the machines was to further force the architectural design to adapt to the limits of the robotic construction system.[99]

2.4 New Phases of Robotics in Architecture

In initial approaches to robotics in construction work, flexibility was further limited because specialized robotic machines could only perform specific construction tasks, depending on what they were designed for.[100] The implementation of a robot in construction was mainly considered a technical problem, to mimic (automate) a manual process, with the aim to increase productivity. However, the result of both specialized machines and standardized robotic construction systems has been to limit design potential.[101]

The renewed interest in robotics in construction comes from the potential of the robot to enable distinct construction and material processes. Recent research projects present high degrees of spatial, formal and structural differentiation that is only possible with a digitally controlled robotic process. Through robotic fabrication, architects have more freedom in design and greater control over fabrication because it offers an interface between data and action, between the virtual and the real.[102] Robotic fabrication provides an open digital platform, and this openness is significant. It can be argued that this high level of data-based openness and adaptability are even more important than the robot's high precision. Using this platform, all processing can be digitalized based on geometric and fabrication logic and different tools can be selected or replaced based on specific manufacturing steps.[103]

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[98] Bonwetsch, "Robotically Assembled Brickwork."
[99] Ibid.
[100] Ibid.
[101] Ibid.
[102] Yuan, Menges, and Leach, *Digital Fabrication*.
[103] Ibid.

2.4.1 A New Dialogue between Design and Making

"Architecture is a material practice that manifests itself in physical reality."[104]

The expression of an architectural creation cannot be assumed to be independent, nor can its material qualities or the processes of its manufacture. Architecture is the result of a process synthesizing both design and making.[105]

The concept of modularization and the use of mass-produced, standardized components that emerged during industrialization have widened the gap between design and making. However, the advance of digital technologies enables, once again, a closer connection between design and making in two ways: first, the conceptualization of architecture through digital design tools, and, second, on the side of production in the form of computer-controlled fabrication tools.[106]

Moreover, the direct control of the building process is enabled by the robot as a programmable universal assembly machine. In other words, "The application of digital technologies is no longer limited to design; it also becomes operative for construction. The direct connection of design data with physical constructive procedures leads to novel design processes based on strategies of fabrication."[107] Therefore, adopting industrial robots with their unique characteristics is of specific interest for architecture these days.

2.4.2 Digital Materiality

As the first architectural application of an industrial robot, the Gantenbein Vineyard Façade, by Gramazio & Kohler, Switzerland, 2006, demonstrates the transition from a manually repetitive to a digital, differentiated robotic fabrication process. Such a complex materialization process cannot be addressed with traditional design methods, instead only becoming controllable and freely formable through computer programming.[108] Such building processes, which made little sense before robots become available in architecture, led to the emergence of a phenomenon that Gramazio and Kohler described a few years ago as "digital materiality." Digital materiality results from the synthesis of data and material that is made possible by robotic fabrication processes.[109]

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[104] Bonwetsch, "Robotically Assembled Brickwork." 7.
[105] Ibid.

[106] Ibid.
[107] Gramazio, Kohler, and Willmann, *The Robotic Touch*. 16.
[108] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[109] Ibid.

The robot will enable a new architectural form of expression by liberating the inherent logic of the material's own properties, whether explicit or implicit.[110] Therefore, materiality and appearance are intimately linked to questions of their making, recalling Gottfried Semper's hypothesis of a "practical aesthetic."[111] Semper drew attention to this "practical aesthetic" in his theory of ornament and clothing, explaining that materiality and appearance are intimately linked to questions of their making. According to Semper, architecture and its material expression cannot be simply invented; they are not something ideal. Instead, they emerge from the relationship between the form and the history of its making.[112] The return of interest in the interrelation of materiality and its performance encourages reconceptualization of Semper's statement and proposes that digital fabrication with the robot can be assumed as a form of "practical aesthetic."[113] The concept of digital materiality addressed though digital fabrication is "constructive," which means that architectural material is never a given, either. Instead, it is always a product broadly enriched by its making.[114] There is an intimate dialogue between digital logic and material, resulting in a highly informed architecture that is committed to details and precise articulation within the whole structure.[115] Therefore, algorithmic design and its materialization (through the robot) result in very striking and rich architectures because they create intense effects, high resolution, and differentiation. The artefacts take on a multipurpose character by changing the view distance, angle of perspective, and light conditions.[116]

2.4.3 Digital Craft

As Gramazio and Kohler effectively define it, "Digital Craft refers to the conceptual integration, that is, the synthesis of digital design and fabrication processes. So digital craft only begins where the architect is enabled to directly intervene in the material processing, giving him or her access to a radically expanded design space."[117]

In the middle of the nineteenth century, a discussion arose regarding the relation between architecture and its making due to the transition from traditional materials to steel, glass, and mass production. John Ruskin discussed the subject in the book, *The Seven Lamps of Architecture*. He drew attention to the nature of materials and their particular processing, and turned against the technical, social, and economic conditions of industrialization. He argued that in traditional handicrafts, two points come together as a whole and manifest visually: the material-constructive and the anthropological aspects of making.[118] As Gramazio and Kohler emphasize in *The Robotic Touch*, "In today's post-industrial world, only a creative use of the mechanic 'interface' makes it possible once again to interweave the material-constructive with the anthropological-individual side of making."[119] In other words, the "craftsman" of the nineteenth century cannot be brought back by the robot; instead, the cultural form and frame of traditional craft can be transformed and redefined through the concept of digital fabrication. In discourses on digital craft, there is an awareness that one should not assume similarity between the robot's anatomy and the human arm.[120]

In summary, a new "craft culture" emerges in architecture by the transformation of architecture's material vocabulary through particular constructive procedures which in turn were a result of articulating a set of parallel algorithmic rules. In other words, digital craft becomes informed by the logic, capabilities, and the conception of robotic machines.[121]

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[110] Ibid.
[111] Ibid.
[112] Ibid.
[113] Ibid.
[114] Ibid.
[115] Ibid.
[116] Ibid.
[117] Ibid. 187.

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[118] John Ruskin, *The Seven Lamps of Architecture*, Dover books on architecture (New York: Dover Publications; London Constable, 1989).
[119] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[120] Gramazio, *Digital Materiality in Architecture*.
[121] Gramazio, Kohler, and Willmann, *The Robotic Touch*.

3. STATE OF THE ART : ROBOTICS IN ASSEMBLY FABRICATION

Additive fabrication with robots allows for the aggregation of very complex and high-performing components out of basic materials at the scale of a building. As can be seen through almost all research and practical, robot-based construction projects in recent years, two features are apparent: a large number of elements and their very detailed organization. In fact, the prospect of using robots to join simple elements into a complex whole becomes not only meaningful, but essential.[122]

The concept of “generic” building elements in robotic assembly should be further described. The simplicity of joining generic elements allows for a vast amount of freedom, so they are very suitable for robotic assembly fabrication.[123] On the contrary, this freedom would not be possible with building elements that limit the freedom of assembly through their specific form. The more specific individual elements become in their geometry, the more their assembly is fundamentally predetermined and, as a result, constructive freedom becomes limited.[124]

In other words, sometimes putting together such elements is easier and faster by hand than by robot. In these cases, the specific added value of the robot would be reduced. It therefore becomes clear why generic elements like bricks, timber slats, or metal bars are the most often used materials in recent robotic assembly projects.[125] Precedents in this regard include the Programmed Wall, Gantenbein Vineyard Façade, Structural Oscillations, the Sequential Wall, the Sequential Roof, Pike Loop, the Stacked Pavilion, and the Programmed Column. With regards to the concept of the final thesis design, the Sequential Wall and Structural Oscillations projects will be analyzed in detail in this chapter.

3.1 The Sequential Wall

The waterproof, loadbearing wall is designed through additive digital fabrication (Figure 15). The design system also allows for insulation, to make the wall suitable as the building envelope. The design was developed to be prototyped as a full-scale wall, at the size of 4 metres wide by 2.5 metres tall.[126]

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[122] Ibid.
[123] Ibid.
[124] Ibid.
[125] Ibid.
[126] Silvan Oesterle, “Performance as a Design Driver in Robotic Timber Construction: A Case Study on the Implications of Material Properties and Construction for an Additive Fabrication Process,” Department of Architecture, ETH, 2009.

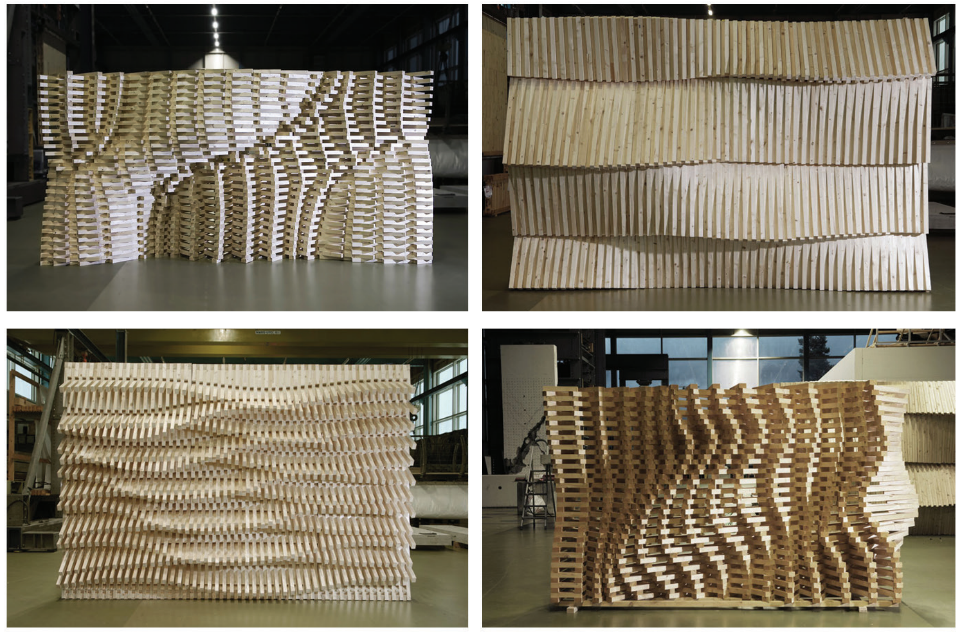

Figure 15. The Sequential Wall, ETH Zurich, Switzerland, 2008-2009.

3.1.1 Aim

The aim of the project was to investigate the design and constructive potential of additive digital fabrication in a timber structure through robotic assembly. The functional requirements of an exterior wooden wall, as well as capabilities, limitations, and logic of the digital assembly process, form the centrepieces of the design criteria.[127] Silvan Oesterle, research leader of the project, believes that it is possible to produce articulate building elements by using advanced digital fabrication technologies. In fact, digital fabrication technologies can be exploited to analyze and transform performance criteria into architectural expression, following the concept of form finding through performance analysis.[128] He adds that “To allow performance criteria to drive the generative parameters of design, custom software tools need to be developed which impart physical aspects of building elements to digital design models”.[129]

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[127] Ibid.
[128] Ibid.
[129] Ibid. 663.

3.1.2 Methodology

According to Oesterle's paper on the above-named research project, the design is developed through three phases, which have framed the methodology of the research project:

1. Define Performance-Driven Criteria: a set of design-driven parameters are defined in order to meet the goal of the project as the building envelope.

2. Mock-up and analysis: models are built and analyzed in order to understand the constructive requirements and logics.

3. Tool Development: physical evolution of the design system is translated into programming code.

Each of these three aspects of the methodology is elaborated below.

3.1.2.1 Define Performance-Driven Criteria

According to Oesterle, the design process was driven by three main sets of parameters, each of which is explained in the following.

1) Material Specifications

Oesterle explains that wood was chosen for several reasons. First of all, it is inexpensive and commonly found in most regions. Second, although it depends on the type of wood and how it is applied, wood has great durability and strength compared to its weight. Third, it is a sustainable material, which has distinguished it in recent years. Fourth, wood can be considered an adjustable component, due to the possibility of processing it into different shapes and lengths. In this project, 40 mm by 60 mm spruce slats with a length of 5 metres were used, which could be cut very quickly with a standard circular saw.[130]

Since weather protection plays an important role in the durability of wooden building structures, the designers decided not to point the face of the wood upward due to potential for water absorption, and areas where rainwater could accumulate were avoided.[131] Overall, material dimensions and material properties formed the first set of parameters that directed the design process, as did the fabrication process, which will be explained below.[132]

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[130] Ibid.
[131] Ibid.
[132] Ibid.

2) Fabrication Process

Fabrication of this project involved a layer-based, additive-stacking process that allowed for a closed structure. A six-axis industrial robot equipped with a custom gripper was chosen as a fabrication tool in order to handle and place the slats at the correct angle and position in space.[133] The slats were connected to each other through a manual nailing system. Since the slats varied from 15 cm to 120 cm in length, a circular saw was used to cut the wood slats. Although the robot was used to mark the length of the slat for cutting, the cutting procedure was kept semi-automatic, with a technician manually cutting the timber slat.[134]

In summary, according to Oesterle, the second set of design-driven parameters was formed by considering the requirements of the fabrication process. They are:

● "A minimum required overlap of half the slat's width between the slats of one layer and the slats of the next layer, which allowed for a proper nailing connection." [135]

● "A maximum allowed cantilever of approximately 70 cm for the overall structure during production in order to avoid sagging and deformation."[136]

● "A placement logic for the slats, either predefined or optimized, which prevented collisions between the gripper and the already built wall."[137]

3) Building-Component Specifications

Besides the previous two sets of parameters for material specifications and the fabrication process, the wall is also designed to function as the building envelope. Therefore, it needed to address specific building performance requirements for negotiating different conditions between indoor and outdoor environments. For example, load-bearing capacities as well as thermal barriers had to be addressed. Cellulose flakes were chosen as the insulation material, to be blown into the hollow core of the wall structure.[138] The cellulose flakes needed to be protected from moisture in order to function as insulation, and a certain degree of air tightness had to be provided by the wood structure.[139] Therefore, building performance requirements determined the third set of performance principles.

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[133] Ibid.
[134] Ibid.
[135] Ibid. 666.
[136] Ibid. 666.
[137] Ibid. 666.
[138] Ibid.
[139] Ibid.

3.1.2.2 Mock-Up and Analysis

Building a model is a valuable tool for the development of a design idea. A physical model helps to understand the constructive requirements and exposes the assembly and sequences logic. Consequently, physical prototyping at scale facilitates addressing limitations in the early stages of design. First, the designers decided to build some of the design sketches at a 1:10 scale.[140] Later, the most developed sketches were built at a 1:1 scale to do a more detailed analysis of structural feasibility and weather protection performance of the system. However, some of the ideas from the 1:10 models could not be translated directly to a 1:1 scale; for example, the stiffness of a glue connection does not translate to the stiffness of a nailing connection.[141]

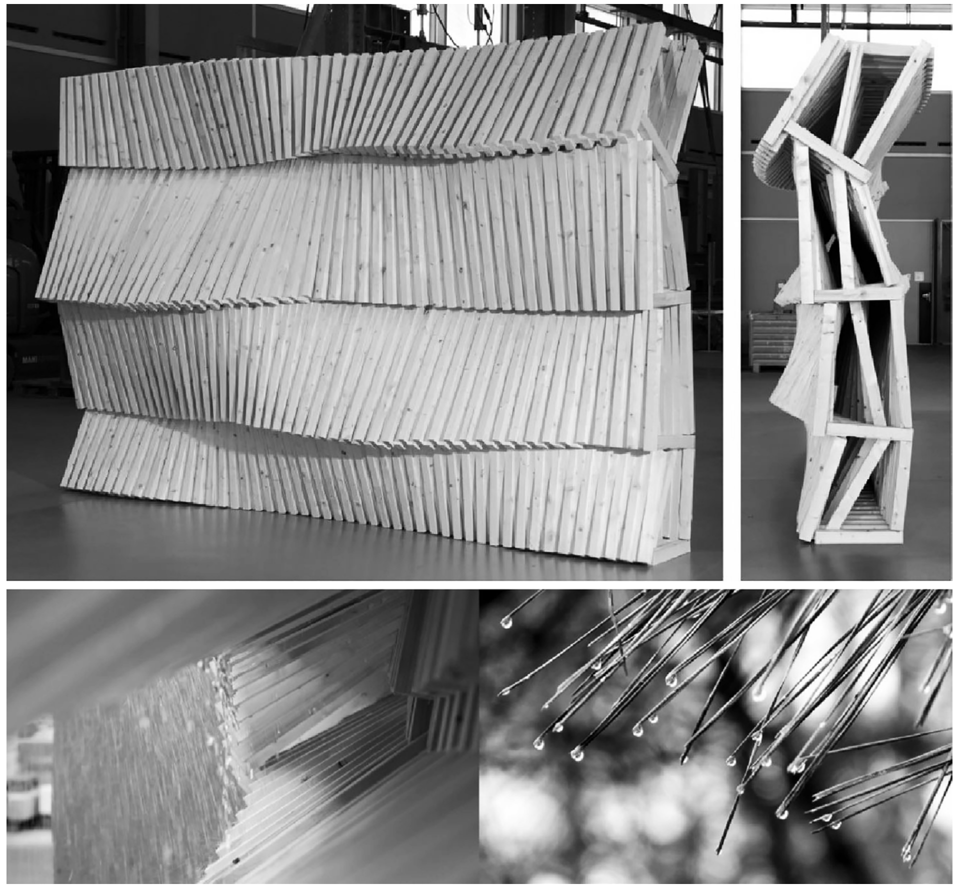

Figure 16. (Top) Project 1, full-scale wall prototype; (bottom) water shielding through sacrificial layer.

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[140] Ibid.
[141] Ibid.

Among all these different approaches, two of those projects that used different design approaches are described. Project 1 (Figure 16) tried to separate the load-bearing, interior part of the wall from the exterior. The ends of the slats stuck out and formed a sacrificial layer.[142] Similar to pine needles, they shielded the bracing part of the wall from rain and drained water away from the hollow core that would hold the insulation.[143] Their face wood always pointed downward to be protected from water. The difference between this project and the next is that in this project, the diverse performance requirements are addressed through different layers that complement and support one another, while project 2 (Figure 17) developed an integrative approach of structure, insulation, and rain protection.[144] The individual performance requirements were addressed through one incorporated system instead of different parts, which in turn resulted in stronger connections, a thicker insulation core, and a better performance of the bracing triangles. [145]

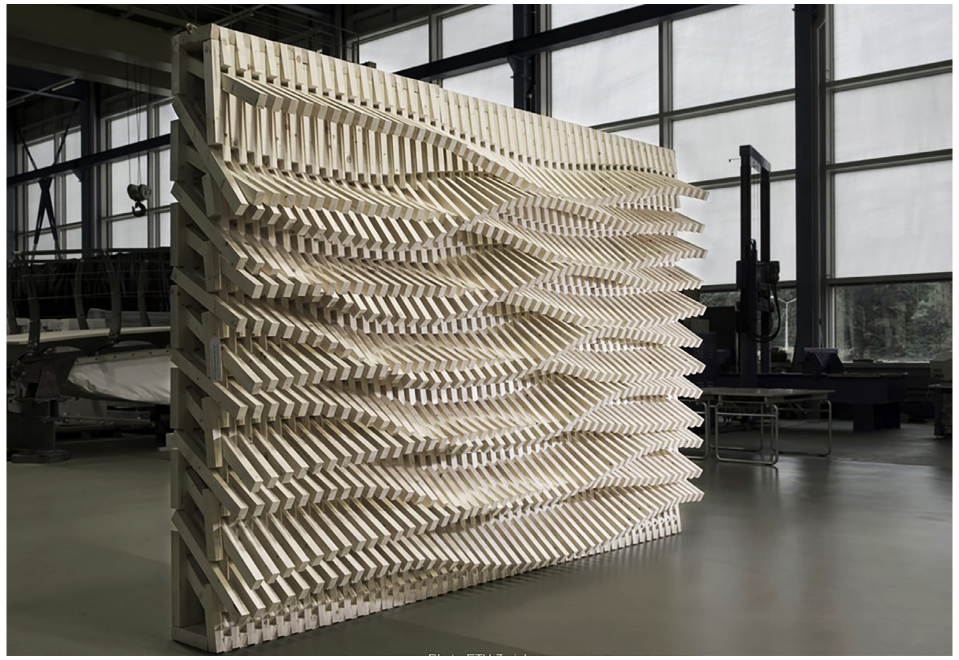

Figure 17. Project 2, full-scale wall prototype.

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[142] Ibid.
[143] Ibid.
[144] Ibid.
[145] Ibid.

3.1.2.3 Tool Development

In order to translate the physical evolution of the design system into programming code, a toolset consisting of two parts had to be set up.[146] The first part consisted of a hierarchical grouping logic of stacking. The whole wall was shaped by the main-level group, and the production layers, which were the actual slat components, formed the sub-group layers. Geometric information like size and position in space and fabrication details formed these groups of information that were attached to the 3D-slat objects.[147] The second part consisted of a custom export functionality that locked on to the grouping hierarchy to extract and read out the additional data attached to the slat components in order to produce the machining code for the robot. It also checked the design for collisions between the gripper and slats, and the slats themselves.[148] Therefore, an immediate translation of design data into production data was possible by through a combination of these two parts. The set-up also allowed producing and testing a wide range of variants for rapid 1:1 robotic prototyping and performance analysis.[149]

3.2 Structural Oscillations

3.2.1 Aim

At the 11th Venice Biennale of Architecture, Gramazio and Kohler conceived of a 100 metre-long brick wall to run as a continuous ribbon through the interior of the Swiss Pavilion (Figure 18). The installation created a new, introverted space that surrounded the four exhibition areas. The wall defined a central space and an interstitial space between the brick wall and the existing structure of the pavilion, and visitors were welcomed to the exhibition passing from one space to the other. The wall was built following algorithmic rules and prefabricated on site at the Giardini by the mobile fabrication ROB Unit.[150]

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[146] Ibid.
[147] Ibid.
[148] Ibid.
[149] Ibid.
[150] Gramazio, Kohler, and Willmann, *The Robotic Touch*.

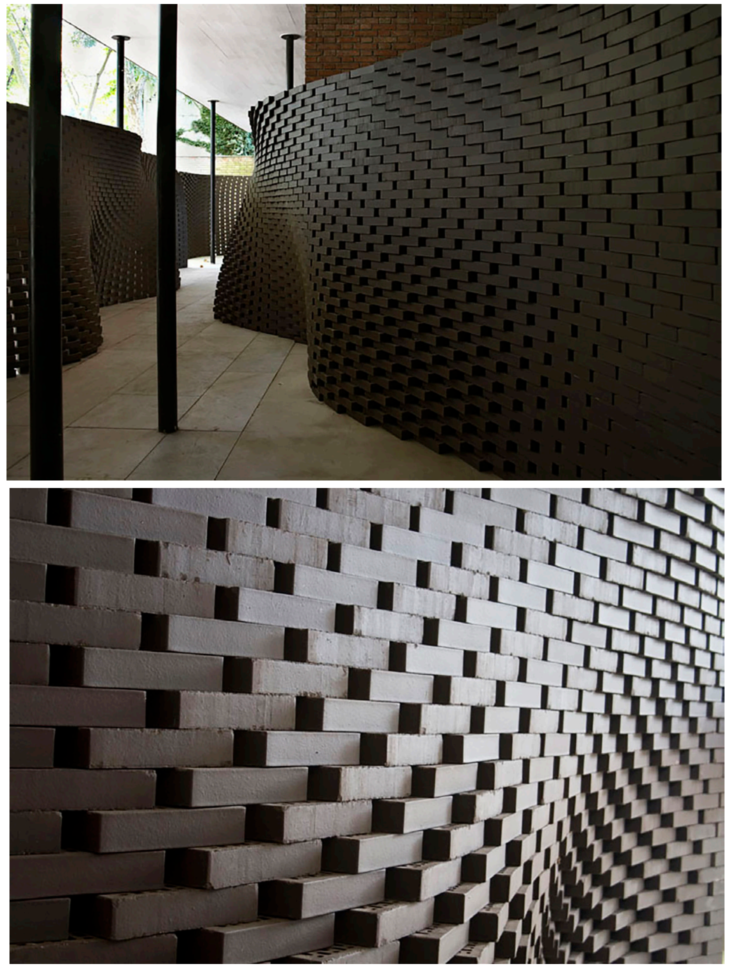

Figure 18. Structural Oscillations, 11th Architecture Biennale, Venice, 2008.

3.2.2 Methodology

According to Bonwetsch's dissertation on the above-named project, the design is based on a simple, continuous curve that defines the path through the pavilion. Its materialization and architectural expression is a direct product of the curve's primary rules set. These rules are derived from four criteria that have framed the final design of the project.[151] In summary, the methodology of this project consists of extracting constructive logic and critical parameters of design and fabrication, which are later summarized as a generative rule set.

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[151] Bonwetsch, "Robotically Assembled Brickwork."

3.2.2.1 Extracting Constructive-Driven Criteria

The four parameters that shape the main under-layered set of rules are:

1. Robotic set-up – ROB Unit

Although the robot and the building are initially spatially separated, the mobile robotic unit ROB, which was put into operation for the production of Structural Oscillations, noticeably changes this situation. As the first ROB Unit field test, it demonstrates the flexibility of a robotic field factory while taking advantage of manufacturing diversity with consistent precision and production quality and with the advantage of short transport distances.[152]

For double-curve elements, this issue becomes more pertinent because their volume-to-weight ratio is significantly higher than straight elements, which can pack more tightly.[153] Since the idea of the ROB Unit dramatically reduces transportation needs, it can be deemed that both economic and ecological factors are presented in the concept of the ROB Unit.[154]

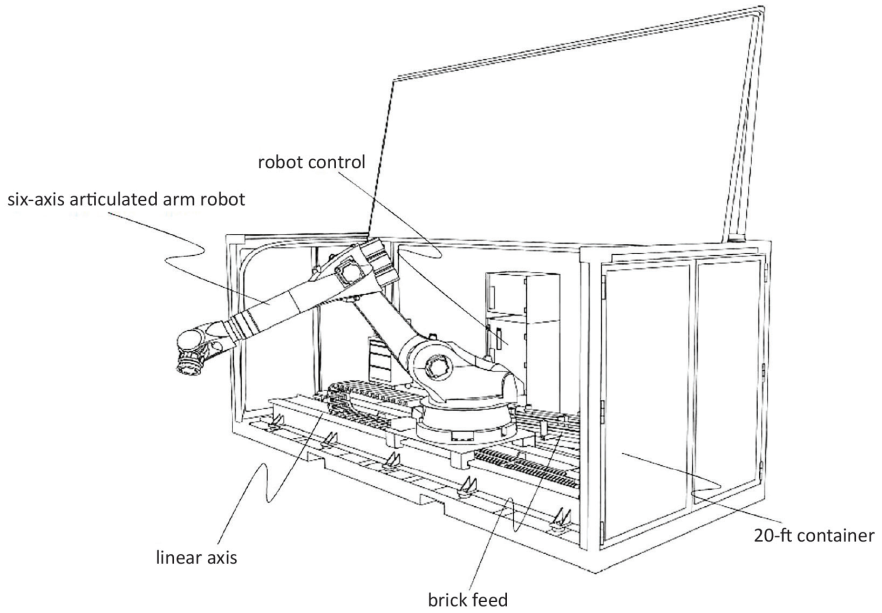

Figure 19. (Top) Conceptual design ROB Unit; (bottom left) ROB Unit assembling a segment of the Structural Oscillation installations; (bottom right) ROB Unit set-up.

The complete robotic set-up of the ROB Unit (Figure 19) is accommodated within a standard cargo container, which allows it to be easily transported. An industrial robot is mounted on a 5-metre-long linear axis and equipped with a control cabinet. The front and top of the container can be swung open, turning the front of the container into a building area reachable by the arm. Peripheral devices installed in the container are as follows: three-brick feeding system that provides three different brick types, a laser sensor that checks if the brick is in position to be picked, a gluing station to apply the structural adhesive, a two-finger parallel gripper as an end-effector, and, finally, the Programmable Logic Controller (PLC), which controls all the in puts and out puts of peripheral devices. Additional security and safety features are required to ensure safety for the operator.[155]

2. Structural Requirements

The initial design was the basic path of the wall through the exhibition, and the final, three-dimensional form was generated as a response to the requirements of statics and stability.[156] To explain the design in detail, the double-curved geometry of the wall should be analyzed from several perspectives.

First of all, the whole wall is produced in 4-metre-long segments, and each segment has to be freestanding, in other words, to stand on its own. As a result, depending on the degree of curvature at a specific location, the footprint of the wall segment is increased in a continuous wave motion, and the stability of the wall segment is thus improved.[157] To further increase its stability, the curvature of the footprint is balanced by a counter curvature in the top layer of the segment (Figure 20). As a final stability check, the centre of mass is located in the footprint of the wall.[158]

Secondly, the stability of the wall structure should be checked not only in its final form, but also during the different stages of the assembly.[159] Support structures are necessary during assembly because the wall segments only become self-supporting once the adhesive has cured. In other words, aspects of the assembly process become critical parameters for the design study. The generic character of the brick allows building up the support

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[152] Isak Worre Foged, ed., *Bricks/systems*, Open Access edition (Aalborg University Press, 2016).

[153] Bonwetsch, "Robotically Assembled Brickwork."
[154] Ibid.
[155] Ibid.
[156] Gramazio, Kohler, and Willmann, *The Robotic Touch*.
[157] Bonwetsch, "Robotically Assembled Brickwork."
[158] Ibid.
[159] Ibid.

structure from bricks without the need to introduce any additional scaffolding. These bricks do not need to be glued. The location and necessary position of the support structure was determined by engineering (Figure 21). The final design data combined with the support structure can then be exported in order to generate the robot control code.[160]

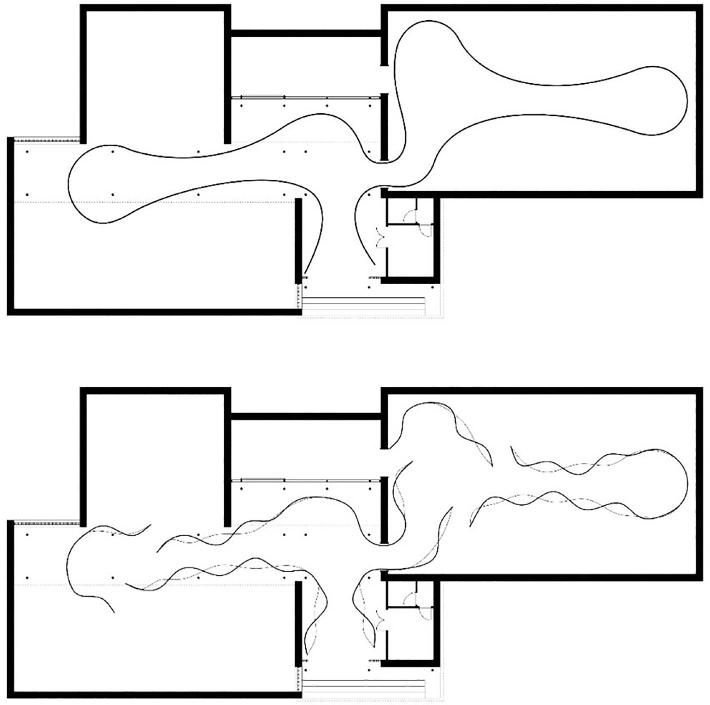

Figure 20. Floor plan of the exhibition pavilion: (top) initial two-dimensional curve; (bottom) resulting double-curved surface generated according to overall stability.

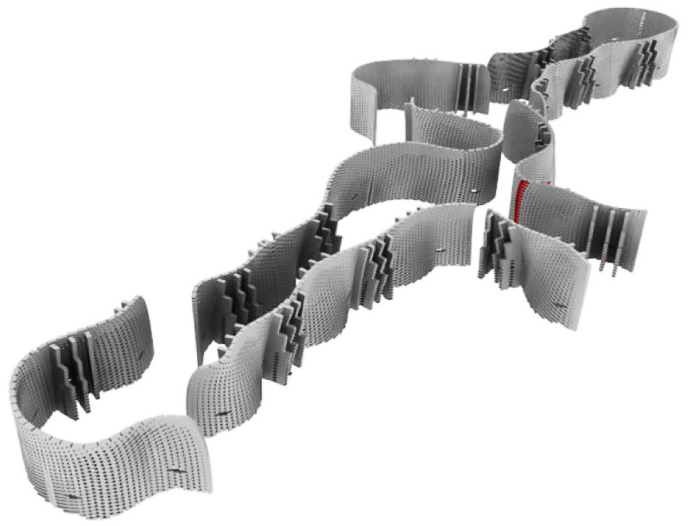

Figure 21. Visualization of the final export data, all wall segments and supports structure.

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[160] Ibid.

3. Material System

A perforated clinker brick with dimensions of 240 x 115 x 52 mm was used. A perforated brick was chosen for two reasons: first, the maximum permitted floor load of the pavilion was limited and the dead load of a wall made from solid brick would have exceeded that limitation. The weight of a perforated brick is approximately twenty percent less compared to a solid brick. Second, perforated bricks have a lower dimensional tolerance than comparable solid bricks.[161] Due to the very precise nature of the robot's job and because several segments needed to be joined later to form a continuous ribbon, it was essential for the layer heights of each wall segment to match at the end.[162]

For bonding, the same structural adhesive, Sikadur-330, used for the Gantenbein winery was used.[163] The adhesive features impressive tensile strength; however, its relatively long curing time of up to twenty-four hours (dependent on temperature) is a major disadvantage. Because of this potentially lengthy curing time, supporting the wall is crucial throughout the assembly process.[164] It also slows down production because brickwork can only be moved from its fabrication location and mounted in place once the adhesive has reached a minimum tensile strength to support the dead weight of the element.[165] Therefore, the robot could not work continuously, and could produce only one element per day.[166]

4. Assembly logic

The computational workflow for the robot control is an abstract description of the brick assembly process. It also includes information on the specific operational space of the hardware set-up, both with regards to the physical layout and communication with external devices.[167] The process can be seen in following diagram (Figure 22).

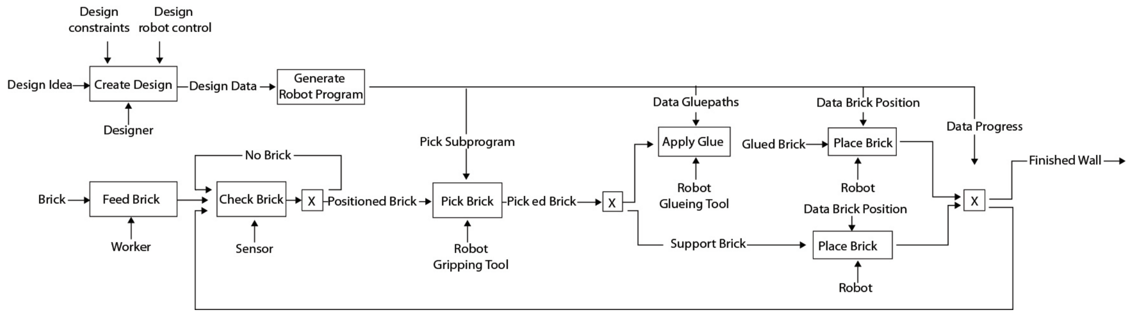

Figure 22. Diagram of assembly process.

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[161] Ibid.
[162] Ibid.
[163] Ibid.
[164] Ibid.
[165] Ibid.
[166] Ibid.
[167] Ibid.

It should be noted that the movement path of the robotic arm for placing support bricks is different from that for placing normal bricks. Normal bricks are placed vertically from above, with 2-millimetre gaps between each brick for the dimensional tolerances of the brick module.[168] Support bricks are positioned from the side until they touch the neighbouring brick to avoid a crash, and they only need to overlap a few millimetres with the brick below.[169] It is also essential to mention that due to the gripper's geometry, the sequence of laying the bricks is important throughout the whole process.[170]

3.3 Conclusions

Both research projects, the Sequential Wall and Structural Oscillations, develop and represent specific outcomes of an integrated digital design and robotic assembly process. While in both projects, the approach builds upon the universal nature of industrial robots as an assembly tool, each of the examples presents a different material and construction system. In both examples, the robot's ability to individually precisely control the positioning of a large number of elements is explored for its architectural design potential. As can be seen with both results, the final designs feature complex geometries and patterns that are enabled by the automation of the processes, highlighting repeatability, precision and consistency. Moreover, for both experiments, there is a bi-directional connection between the design and its execution. In other words, while the parameters of the robotic assembly process affect the design, the assembly process itself can be formed according to a definite design intent.

In both experiments, the knowledge of making was abstracted and codified, which in turn included material properties and constructive principles. For example, in order to create a working brick system in Structural Oscillations, the specific placement and bonding logic was classified and ordered to create a robust brickwork bonding logic. This included the minimum and maximum overlap of bricks, the required minimum gap to avoid collisions, or the need for control over the stability of the wall during the build-up process. This considerations resulted in the parallel assembly of a brick support structure as part of the wall that prevented the wall from collapsing during assembly.

Moreover, in both designs the material bonding technology was developed to correspond to the robotic assembly process. For example, in Structural Oscillations, structural adhesive was applied for bonding instead of mortar. While applying adhesive is common practice in industry, using it as a bonding material resulted in novel structural possibilities. In traditional manual brickwork, brick and mortar act as a compression-only structure, while the tensile strength of the adhesive allows for new possibilities in the brick structure. This structure is well suited for prefabrication, as the prefabricated panels can be easily transported and installed with no need for further reinforcement.

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[168] Ibid.
[169] Ibid.
[170] Ibid.

As can be seen in these precedents, design data reflects the logic of assembly and is closely connected to the tools and process of its physical execution. The robotic set-up itself is a matter to change. The robot can also be equipped with completely different end-effector tools and peripheral devices. Therefore, any changes in set-up and tool strategies can open completely new possibilities and limitations in the process, which are consequently all relevant to the design. As a result, the robotic set-up and peripheral tools are clearly defined in the design steps.

Finally, for both projects, a computational method was used in order to achieve a closer link between the design data and the control data of the robot. The very large number of elements can hardly be captured in a static drawing. There are also many dependencies that become apparent in the design system that in turn can affect other items, and the logic of dependencies can only be handled through computational methods. For example, in Structural Oscillations, the size of the curvature can affect the size of the brick, and, as a result, the gap between bricks. Computational design makes possible that design data and robot control are developed step by step. The constructive system, the robotic set-up, and the assembly logic sequentially come together and frame the final script, in which the design and assembly processes are synchronized.

4.DESIGN: ROBOTIC ASSEMBLY OF TIMBER STRUCTURES THROUGH STANDARD & NON-STANDARD COMPONENTS

4.1 Aim

The design and fabrication of a non-standard, double-curvature timber structure through standard elements forms the centrepiece of this thesis. The research developed a robotic-based production method for building a complex, free-form structure that seemed impossible through conventional construction methods. The aim of the research is to develop novel architectural potential by synchronizing digital design with a robotic assembly process. Through the experiment, both the design and the process of making were seen as integral parts that correspondingly informed one another. The experiment also sought to demonstrate the capacity of producing variability and differentiation through scripting design and robotic assembly of standard components with no additional expenses, compared to typical manual construction.

The idea is to consider the design aspects of the unique, complex geometrical form of an architectural element at the same time as real-world demands in terms of materiality, construction, economy, and environmental concerns. It is essential to apply real-world parameters as important criteria driving the design, with the aim to potentially impact common building practice.

The goal is to develop an assembly system that can be adaptable to various architectural applications. The system can be used to form a wall that creates a space, with a unique complex geometry that meets the requirements of a stand–alone structure or it can be oriented differently to act as a non load-bearing ceiling structure or as furniture. The potential of the system to act as a functional component that can play a role as a load-bearing structure was also investigated. Another objective is to explore a system that creates possibilities for the wall to be built and manufactured at various scales, in diverse locations, and hosting different functions; as either an interior or exterior installation; and as an interior separator or the screen on a façade.

Ultimately, the design is planned for building the complex geometry of the wall using standard elements that are already on the market or can be processed in a short time and as part of final robotic fabrication. However, the concept is to benefit the ability of robotic assembly in architecture and construction, creating differentiation and variability through the standard modular element. In other words, using the industrial robot is not for mass production but for mass producing unique applications, therefore establishing a closer link between non-standard design and contemporary building practice. The thesis presents two full-scale prototypes, demonstrating different applications, which are fabricated with the robot arm at a 1:1 scale.

4.2 Methodology

The aim of this research, as mentioned before, is to design and prototype a double-curvature timber structure produced from standard and non-standard elements through an additive, digital fabrication process. The methodology to achieve this goal can be described simply in three major steps, as follows:

1. Analysis of precedents' systems and strategies; study of design-driven criteria;
2. Redefinition of design-driven criteria according to research project goals; analysis of material choice, definition of wall specification according to wall function and objective, extraction of fabrication parameters and limitations;
3. Design of a new system according to new design-driven criteria.

In both precedents, the Sequential Wall and Structural Oscillations, described in Chapter 3, the project design was developed according to a set of rules extracted through an earlier analysis of project material choices, building-component specifications, and fabrication parameters. To understand the connection between those design-driven criteria and the final design, it is important to begin with a layer analysis of the Sequential Wall as one of the precedents (Figure 23).

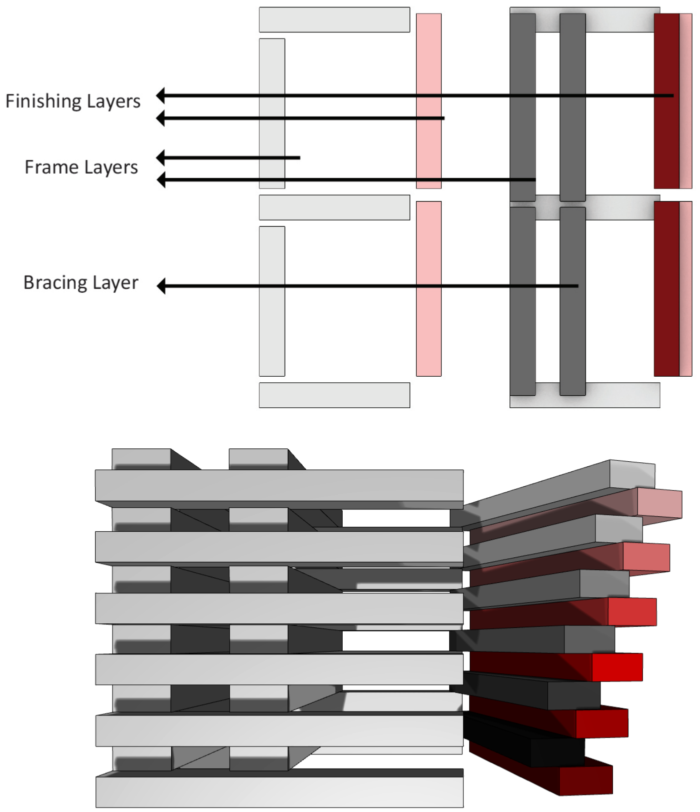

Figure 23. Analysis of Sequential Wall: (top) side view, main layers of the structure; (bottom) sacking as fabrication method.

As can be seen in following figure (Figure 24), this re-modelling can be summarized as follows:

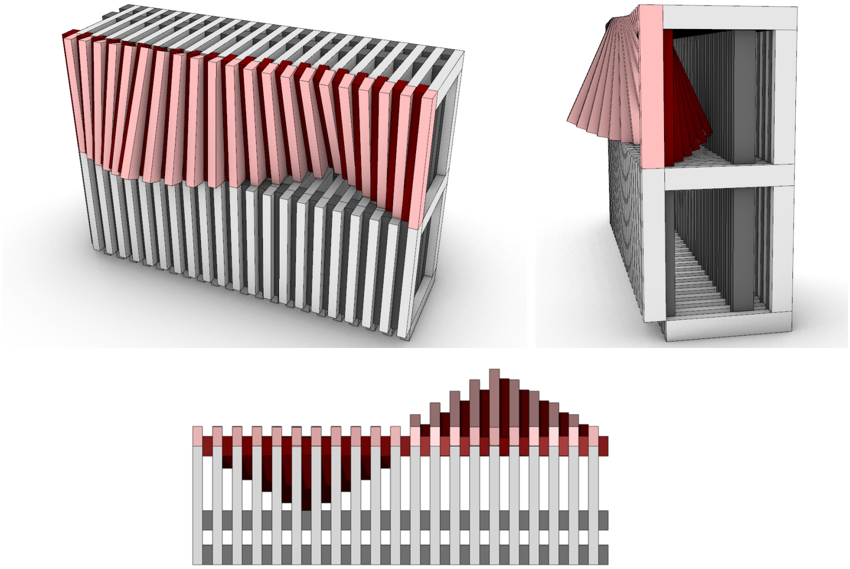

Figure 24. Analysis of Sequential Wall, main layers: (top left) perspective view; (top right) perspective view; (bottom) Plan view.

- Material Choice: Timber slat – adjustable generic component
- Wall Specification: In order to meet the requirements of the design as an exterior wooden wall, the system is framed with three major layers:
    - Frame layer (in order to address stability)
    - Bracing layer
    - Finishing layer (in order to address envelope functionality)

- Fabrication Method: Additive stacking is chosen because it allows for the aggregation of a very complex building component out of simple materials. It should also be noted that the structure and fabrication method set some constraints for the design system; for instance:
    - A minimum required overlap
    - A maximum allowed cantilever to avoid sagging and deformation
    - A placement logic for elements with regard to the gripper specification and with attention to avoiding collisions between the gripper and the previously built parts of the wall

It can be concluded that the layer analysis of the Sequential Wall project assists in understanding how the design system can be formed through design-driven parameters.

In the second step, the design-driven criteria are extracted according to the project's requirements and limitations. Similar to the precedents and, as already mentioned, this study focuses on three areas: material alternatives, structural stability, and fabrication parameters.

Regarding material choice, one of the main ideas is to choose the material from among simple, standard elements with respect to the concept of "genericness" described in the context chapter, Chapter 2. Timber slat is chosen from among alternatives such as brick, concrete block, and metal bars for several reasons described in detail below in section 4.3, Material System.

To extract the required specifications for the concept wall, the wall function should, first of all, be defined according to the concept goals of the project. To start, the necessity of a self-supporting structure, as well as aesthetic aspects, play essential roles for the timber structure's performance as an interior separator or exterior installation. Therefore, these two aspects become part of the main design-driven criteria that are described in detail in section 4.4, Design System. This section also describes how the potential of the system can be explored and developed to integrate secondary functions. This integration can allow for additional functional requirements to be addressed directly in the design system within the computational model.

Following the new dialogue between design and making in architecture, previously discussed in the context chapter (Chapter 2), the fabrication criteria and process are integrated into the design process at an early stage. The robot set–up and peripheral devices are considered as critical parameters in the design process. The physical boundaries and limitations on where and how the robot can operate are defined according to the robot model, its reach and payload, the end-effector tool, peripheral devices, and their spatial layout set. These tools, specifications, and features will directly affect the design strategy. Besides the assembly, other fabrication processes such as gluing, cutting, or drilling, as well as the feeding strategy, should be defined in the design process. Each of these stages could be manually added to the process or become part of an automated fabrication system.

In summary, all essential parameters and limitations extracted through a study of the material system and fabrication method frame the design-driven criteria, which in turn outline the set of rules for the design system. These parameters and how they form the final design system are described and illustrated in detail in the next two sections.

4.3 Material System

In the material system of this research project, the two main materials are the timber slat and the structural adhesive, described below.

4.3.1 Timber Slat as Principal Member

Wood has recently become a mesmerizing building material in architecture. Timber slats are thus chosen as the material for the research project. Wood embodies a rich history and cultural roots and, at the same time, provides prospects for the future built environment. However, the dominant role of wood was increasingly challenged in the construction industry with the dawn of industrialization, as compared to steel and concrete. As technological advances have developed new production processes in recent years, traditional conceptions about wood have changed. This includes new approaches to design computation and simulation, as well as robotic timber manufacturing.[171] As Achim Menges, Tobias Schwinn, and Oliver David Krieg note, "with the help of computational design, and computer controlled manufacturing, wood – one of the oldest construction materials we have – can now be rediscovered as a natural, high-performance fiber composite material."[172] Other aspects of wood as a material for this project are as follows:

1. Environmental Aspect: Wood as Biological Building Material

About thirty percent of all worldwide land area, 3.9 billion hectares, is covered with forests.[173] With the right policies and rules, this can be considered a vast, potentially fully renewable resource. Wood can be considered not only as a final product, but also for its conversion of carbon dioxide into oxygen during its natural growth. Wood products have a very low level of embodied energy and at the same time have a positive carbon footprint. For example, a panel with a given compressive strength in wood requires 500 times less energy than one in steel.[174] Therefore, as one of the few ecologically sound building materials, wood has found a new role among building materials due to the severe environmental challenges that we are experiencing these days.

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[171] Menges, Schwinn, and Krieg, *Advancing Wood Architecture*.
[172] Yuan, Menges, and Leach, *Digital Fabrication*, 115-116.
[173] Menges, Schwinn, and Krieg, *Advancing Wood Architecture*.
[174] Ibid.

2. Structural Aspect: Strength-to-Weight Ratio

Depending on the type of wood and how it is applied, it possesses great durability and strength compared to its weight. Considering weight as an important factor of structures, wood has almost the same compressive strength as concrete and the same tensile loading capacity as steel.[175] With this impressive strength-to-weight ratio, timber has become a high-performance material in the building industry.

From the perspective of this project, while structural strength is significant, weight plays one of the main roles. As is the case in many robotic assembly projects, robot-based construction processes are usually characterized by a large number of elements and their very detailed organization. This huge number of elements may makes the structure very heavy and, consequently, may make transportation of prefabricated panels difficult. Therefore, minimizing the weight of the material is of significance, and timber slats have this advantage compared to other potential assembly materials like brick.

3. Genericness: Timber Slat as a Simple Generic Element

By putting generic elements together and creating highly informed and differentiated architectural assemblies, the application of the robot becomes meaningful and essential. The formal simplicity of generic elements is highlighted in contrast to the complex geometry achieved by the robot's positioning. Additionally, the generic element's lack of embedded assembly instructions allows for a vast degree of freedom in assemblies, which would not be possible with building elements that might limit the freedom of assembly through a specific form.

While timber slat is generic, it allows the manipulation of its geometry during the fabrication process. Each element can be easily cut to a specific length and, if needed, to any angle. Through the potential of material customization available in timber slat, a standard industrial product is transformed into a particular and unique architectural element. As a result, additional degrees of freedom are added to the constructive system, which is very valuable.

As a result, timber slat, as an adjustable generic component, was determined to be a very suitable material choice. The standard 1" x 2" timber slat was chosen.

4. Other Key Aspects

There are several other remarkable features that make wood interesting in this context. Wood is relatively inexpensive compared to other building materials, which is of considerable value. Moreover, the ever-expanding design possibilities in wood structure applications make this material different and unique.

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[175] Ibid.

4.3.2 Structural Adhesive as Joining Material

While the same structural adhesive that is used in robotic assembly brickwork research projects (i.e. Programmed Wall, Structural Oscillations, and Gantenbein Vineyard Façade) might be for gluing in this research project, a simple wood glue was used at this early stage of the physical experiments.

According to details in Bonwetsch's dissertation research, a commercially available, structural adhesive was applied for gluing. The structural adhesive applied is Sikadur®-30, the adhesive for bonding reinforcement.[176]

According to the product data sheet provided by AKSID Corporation for this material, Sikadur®-30 is a thixotropic, structural, two-part adhesive, based on a combination of epoxy resins and special filler, designed for use at normal temperatures between +8°C and +35°C.[177] This two-part, epoxy-based adhesive is intended specifically for use in construction applications with various materials (e.g. concrete, bricks, timber, etc.). In particular, for non-standard geometries that do not act as compression-only structures, the adhesive can provide additional tensile reinforcement for the whole structure.[178] Since this research project is focused on non-standard surfaces and complex geometries, this high-strength adhesive can potentially account for tensile forces.

For this thesis project, the adhesive in combination with the timber slats must be able to transfer both shear and tension forces. Preliminary tests with the wood glue adhesive appear to indicate sufficient mechanical performance, and faster curing times than Sikadur, which render it feasible for the timber slat application. It is important to mention that the connection also needs to tolerate dynamic forces during transportation, since part of the concept is to prefabricate the wall elements and transport them to site. Therefore, choosing the appropriate bonding system is important.

Applying the adhesive can be done either manually or automatically during the fabrication process. It should be noted that, with regard to which process should be considered, different products with the same performance could be used.

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[176] Bonwetsch, "Robotically Assembled Brickwork."

[177] "Product Data Sheet," AKSID Corporation, Last modified December 2017, Available from: https://can.sika.com/content/canada/main/en/solutions_products/document_download/Sikadur_PDS_Alpha.html

[178] Bonwetsch, "Robotically Assembled Brickwork."

4.4 Design System (Fundamental Parameters of Design – Design-Driven Criteria)

The goal of this thesis project is to design and fabricate a double-curvature timber structure through additive manufacturing of standard and non-standard elements using a robot arm. As mentioned in the methodology section (4.2), and similar to other precedents, the key requirements of the design and assembly parameters frame the design-driven criteria. These result in the step-by-step development of a system that addresses the design preferences and concept. The design system begins to be shaped according to the fabrication technique (additive-stacking robotic assembly) and essential criteria like structural aspects. However, other parameters, which are listed below, lead to the development and improvement of the system.

4.4.1 Additive-Stacking Fabrication Technique

An additive-stacking fabrication technique is chosen for this research experiment, similar to the Sequential series project and all robotic assembly brick work examples. Although spatial timber assemblies have been explored in several recent projects with significant results, this project uses a stacking technique for its simplicity as an entry point into robotic assembly fabrication (Figure 25).

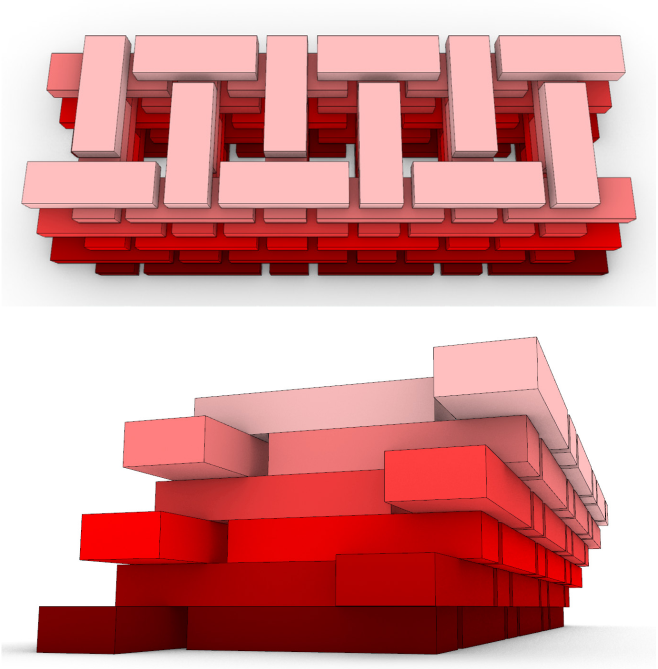


Figure 25. Additive-stacking as the proposed fabrication method:
(top) top perspectve view; (bottom) perspective view.

4.4.2 Self-Stability Capability

In the Structural Oscillations project, a support wall was needed throughout assembly and at some parts of the whole structure to guarantee its stability. However, the key aim of this thesis research is to develop a structure system that is self supporting both throughout assembly and as a final structure. In order to address the required stability, the bonding strategy is explored as both a design step as well as part of the assembly process. Therefore, the connection system and overlapping arrangement of elements play a significant role in the structural system. As mentioned in the methodology section (4.2), the first design exploration starts with remodelling and a layered analysis of the Sequential Wall as an additive-stacking precedent. While the double-face structure and the required connection of these two faces shape the general system, the essential consistency and consolidation of the overall structure should be investigated through the capacities and limitations of overlapping and connection of elements. Two approaches are investigated below.

First Approach: "L" Configuration System

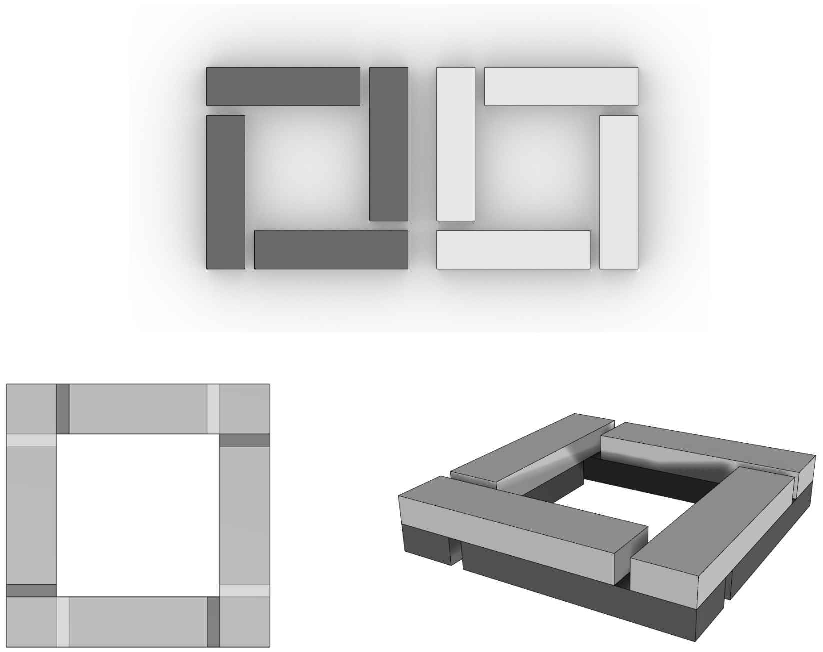


Figure 26. "L"configuration approach, layer system: (top) plan view, layer 1 & layer 2; (bottom left) plan view, overlapping of layer 1 & layer 2; (bottom right) perspective view, overlapping of layer 1 & layer 2.

The system proposed in the first approach, the "L" configuration system (Figure 26), has both advantages and limitations, as discussed below (Figures 27-29).

- Potentials:
  1. The gap between each element allows for rotation.
  2. The placement strategy allows a constant connection between elements in layers below and above.

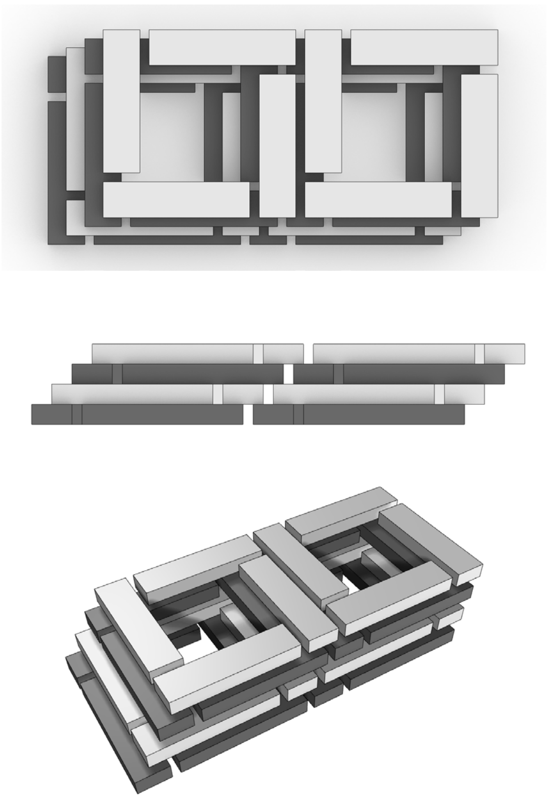


Figure 27. "L" configuration approach, layer system & overlapping: (top) plan view; (middle) front view; (bottom) perspective view.

- Limitations:
  1. Although the system allows a constant connection between elements in layers below and above, the width of the element creates a slight overlap with those beside it.
  2. The slight overlap of elements with those beside it, with no space for a gap, will also be an issue for the assembly process considering the limitations and requirements of the two-finger gripper.
  3. The limitations of shifting in and out due to the element's width will also limit the vertical curvature size.

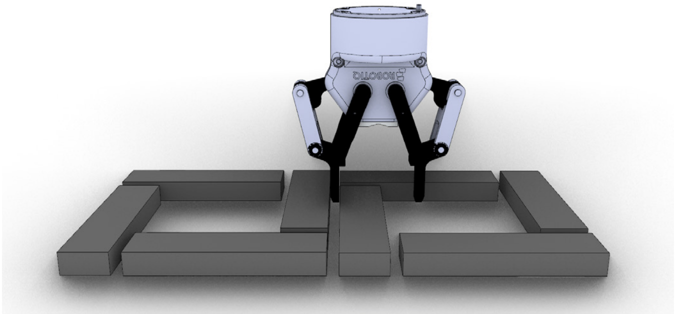
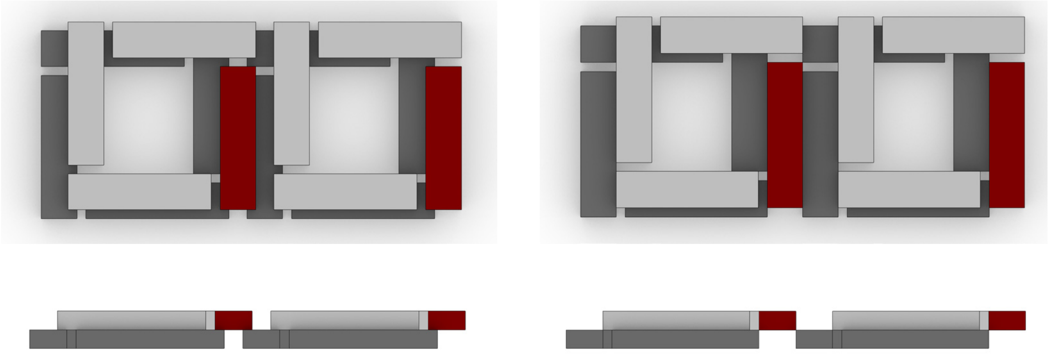


Figure 28. Possible collision error for placing of component in "L" configuration approach.



Model 1

Model 2

Figure 29. Overlap and gap limitation issue for "L" configuration approach: (top) top plan views; (bottom) front views.

Second Approach: “T” Configuration System

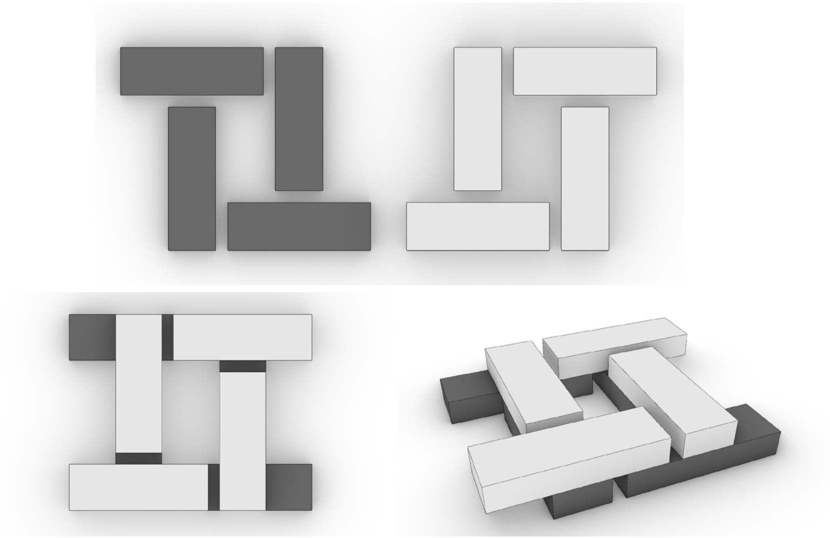


Figure 30. "T" configuration approach, layer system: (top) plan view, layer 1 & layer 2; (bottom left) plan view, overlapping of layer 1 & layer 2; (bottom right) perspective view.

- Potentials (Figures 30-36):
  1. It is a possible to play with the gap size in the design because of the placement system for elements.
  2. The gap between each element allows for rotation.
  3. The placement strategy allows for a suitable connection between elements not only with layers below and above but also with those to the side. Therefore, the system can address the required consistency and consolidation of the whole structure.
  4. The so-called T’s tail in the system works like a stud wall for the structure and creates stability.
  5. The so-called T’s tail in the system also allows for a larger vertical curvature size in the design.
  6. The system strategy works with the requirements and limitations of the external two-finger gripper shape in the assembly process.

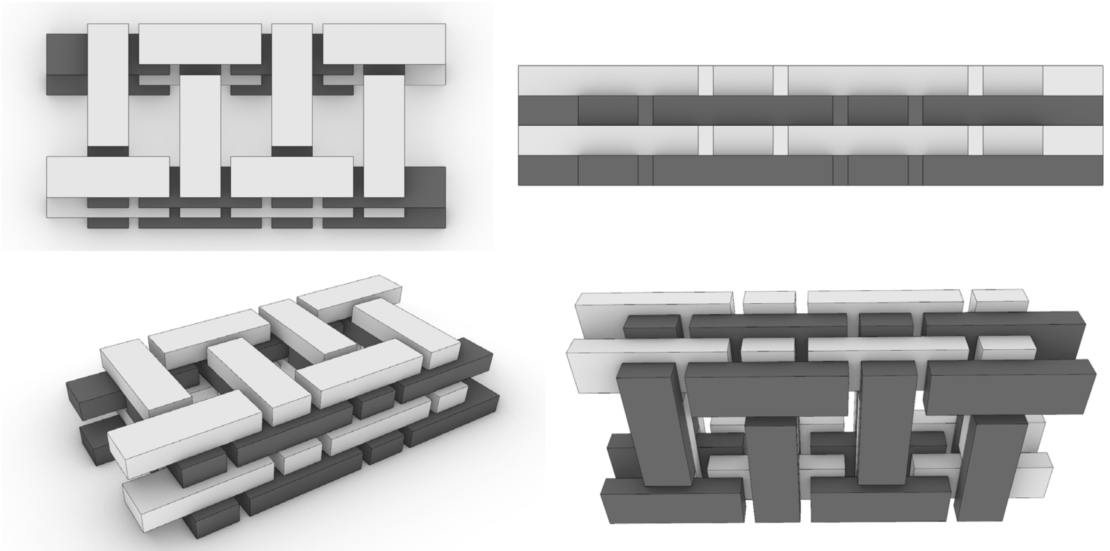


Figure 31. "T" configuration approach, layers system & overlapping: (top left) plan view; (top right) front view; (bottom left) top perspective view ; (bottom -right) bottom perspective view.

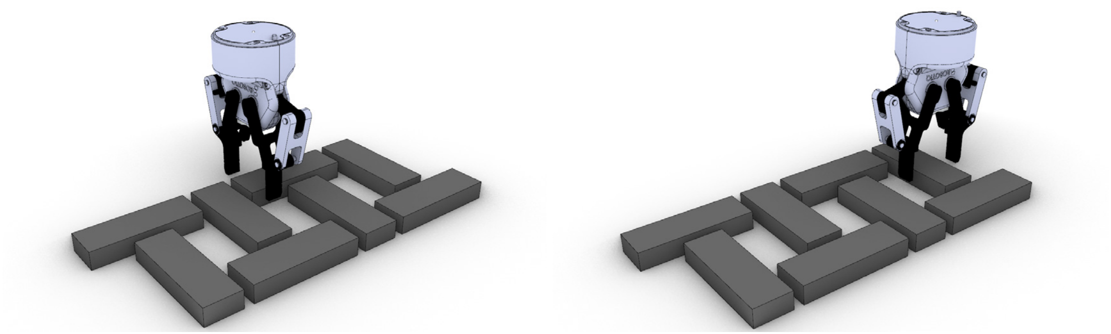
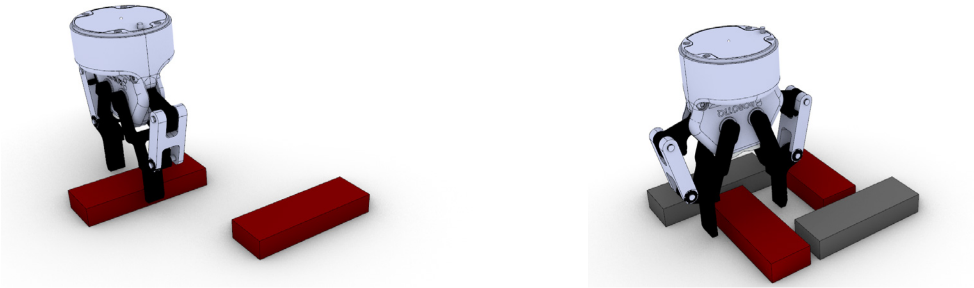
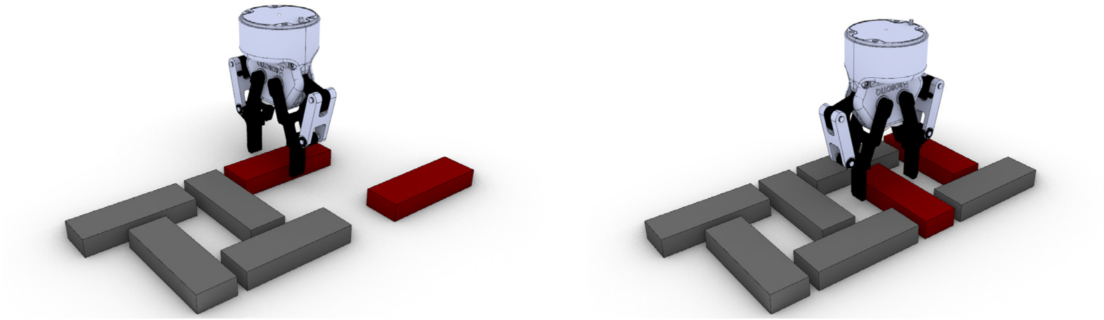


Figure 32. Proposed placing strategy for " T" configuration approach : (left) placing of the so-called T's head; (right) placing of the so-called T's tail.



Assembly order # 1, so-called T's head

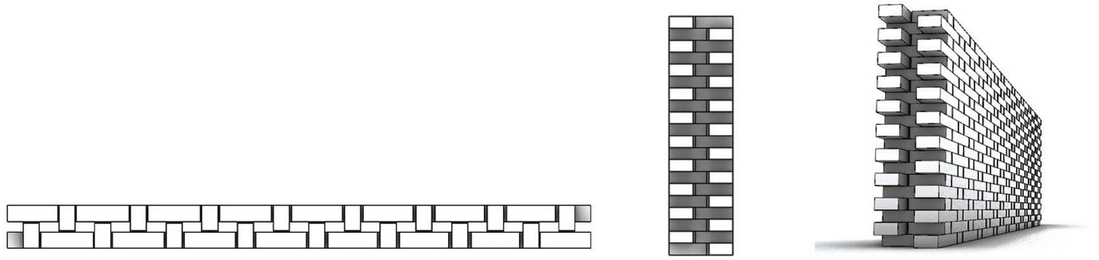
Assembly order # 2, so-called T's tail



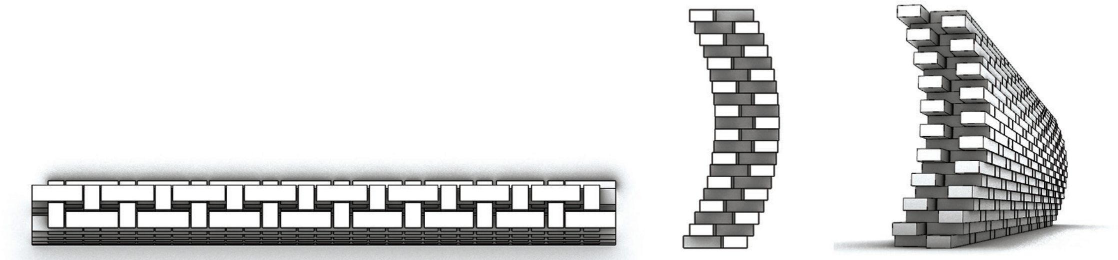
Assembly order # 3, so-called T's head

Assembly order # 4, so-called T's tail

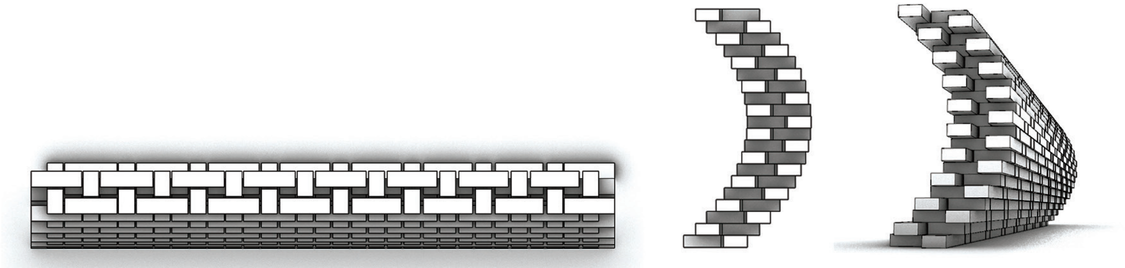
Figure 33. Proposed placing strategy orders for "T" configuration system in order to prevent collision.



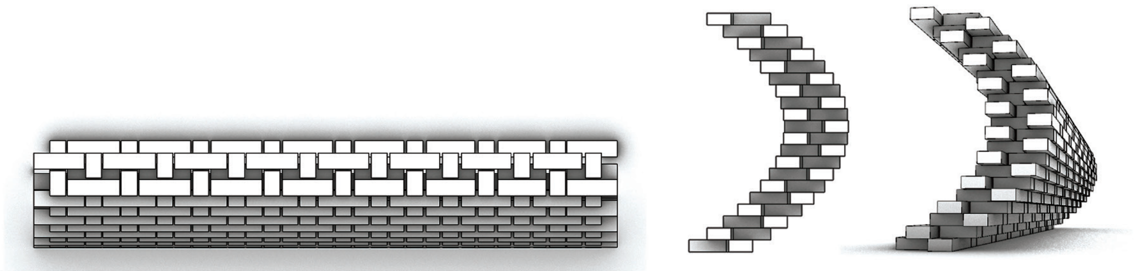
Wall # 1 Plan View Side view Perspective view



Wall # 2 Plan View Side view Perspective view



Wall # 3 Plan View Side view Perspective view



Wall # 4 Plan View Side view Perspective view

Figure 34. "T" configuration system, so-called T's tail allows for the possibility of larger vertical curvature size.

In sum, the second approach meets the consideration of stability of the timber structure and, at the same time, does not limit the design geometry. It will also work later in the assembly process with the limitations and requirements of the two-finger gripper.

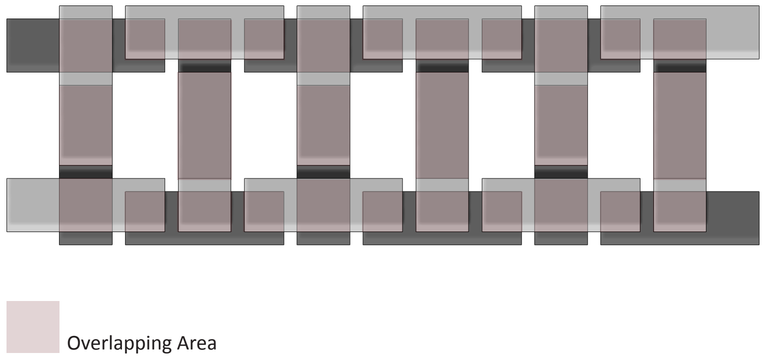


Figure 35. "T" configuration system, possible overlapping that would result in consistency of the overall structure.

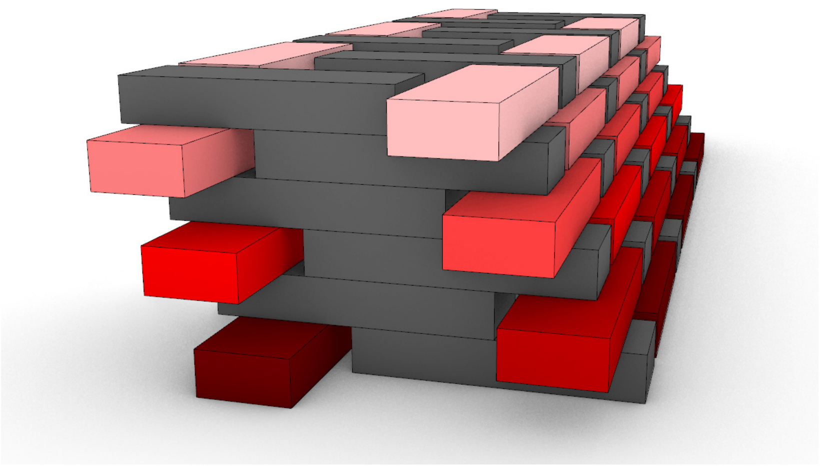


Figure 36. "T" configuration system creating two major layers of structure and finishes in the structure.The so-called T's tails work as bracing structure and the so-called T's heads work as finish layers.

4.4.3 Structural Component Capability

In order to behave structurally, a structure should be designed to withstand the forces transferred through it. These loads are of two categories:

1. Gravity (service) loads, i.e. Dead, Live, and Snow loads.
2. Lateral loads, i.e. Wind and Seismic loads.

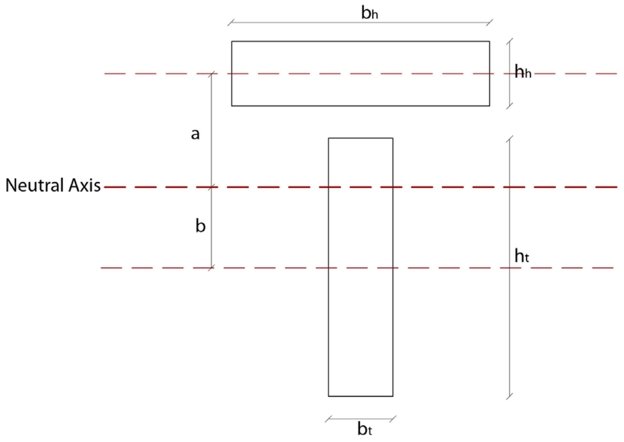


Figure 37. "T" configuration structural modules.

Gravity Capacity

The structure's axial force capacity, P_r, depends on two major factors based on the equation (4-1).[179] material and geometry.

The materials of the structure include wood and the adhesive component. These materials should be chosen based on the required strength (compressive, shear, and tensile) with respect to applied forces to the wall.

Geometry wise, according to the equation (4-1), the structure's Slenderness and the Ratio of Overlapped-Area are the two major parameters.

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[179]

Regarding the structure's Slenderness, the T's tails (web) provides out-of-plane stiffness. The webs also transfer the shear flow between the T's heads due to the out-of-plane bending moment. The longer the T's tail, the larger the out-of-plane bending capacity and the smaller the slenderness. The structure's lateral stiffness is directly related to the out-of-plane moment of inertia. In other words, the higher the moment of inertia, the greater the structure's stiffness and axial force capacity. The moment of inertia of the structure I_T is calculated by the following equations[180](Figure 37):

$$I_h = \frac{b_h \times {h_h}^3}{12} + (b_h \times h_h) \times a^2$$

$$I_t = \frac{b_t \times {h_t}^3}{12} + (b_t \times h_t) \times b^2$$

$$I_T = I_t + I_h$$

I_h: Moment of Inertia of T's "Head" about the T's Natural Axis (NA)
I_t: Moment of Inertia of T's "Tail" about the T's NA
I_T: Moment of Inertia of the "T" Module about the T's NA
a: distance between centre of gravity of the Head and T's NA

b: distance between centre of gravity of the Tail and T's NA

According to the above equation, h_h, h_t, a, and b play a significant role in I_T. However, since $h_t >> h_h$ and a>>b, the most effective way to increase I_T is to increase h_t and "a," which can be achieved by increasing the T's tail length. Based on the demand I_T, the optimum required thickness of the structure in each layer can be calculated from the above equation.

Regarding the Ratio of Overlapped-Area, gravity forces transfer perpendicular to wood slats from one course to the adjacent course through the overlapped area between timber slats. The Axial capacity of a structure (P_r) is directly proportional to the area of overlapped timber slat and the "Factored Compressive Strength" of the wood and the adhesive material ϕF_c.

$P_r \alpha \rho_i \times A_i$

$P_r \alpha \phi F_c$

$P_r \alpha K_c$
P_r: Factored Compressive Capacity of the structure (N)
ρ_i: Ratio of Overlapped-Area of timber slats between layer i and i+1
A_i: Total area of timber slats in row i (mm^2)
ϕF_c: Factored Compressive Strength of wood and the adhesive material (MPa)
K_c: Slenderness Factor, which is directly proportional to the structure's out-of-plane moment of inertia I_T

$P_r = \rho_i \times A_i \times \phi F_c \times K_c$ (4-1)

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[180] Ferdinand P. Beer, E. Russell Johnston and David F. Mazurek, *Vector Mechanics for Engineers: Statics and Dynamics*.

Shear Capacity

According to the equation (4-2),[181] the structure's Shear Capacity depends on its materials and geometry. Lateral forces transfer parallel to wood slats from one course to the adjacent course through the overlapped area between timber slats. The Shear Capacity of a wall V_r is directly proportional to the area of the overlapped timber slat and "Shear Capacity of the adhesive material" ϑ_g.

V_r: Factored Shear Capacity of the structure

$V_r \alpha \rho_i \times A_i$

$V_r \alpha \vartheta_a$

ϑ_g: Shear Capacity of the adhesive material

$V_r = \rho_i \times A_i \times \vartheta_a$ (4-2)

To conclude, the "T" layout mechanism in the structure's geometry is a very effective pattern and efficient for addressing its structural capacity.

It should be noted that, ρ_{ig} and ρ_{is} (the minimum required overlap ratio for axial and shear forces in course i respectively) can be derived based on applied forces to the structure.

The maximum of the above parameters will be defined as thresholds in the script for the proposed structure, as described in more detail and through diagrams in the computational system section.

4.4.4 Aesthetics

As a secondary goal, this project explores the possibilities of the system that can add value in aesthetic terms and offer more freedom in design. The first value could be the potential of thickness differentiation in the design. As can be seen in the diagram, the so-called T's tail strategy in the system provides the opportunity to change the thickness of the structure by changing the size of the tail element. The T's tail has a free head direction from one side; therefore, its length can be changed. However, it should be noted that this size variation option in the design opens a completely new discussion with challenges regarding the procedure that should be added to the assembly process, which would be at the cutting stage. Each element would need to be cut to the specific defined length before assembly (Figures 38 & 40).

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[181] Canadian Wood Council, *Wood Design Manual,* 2010.

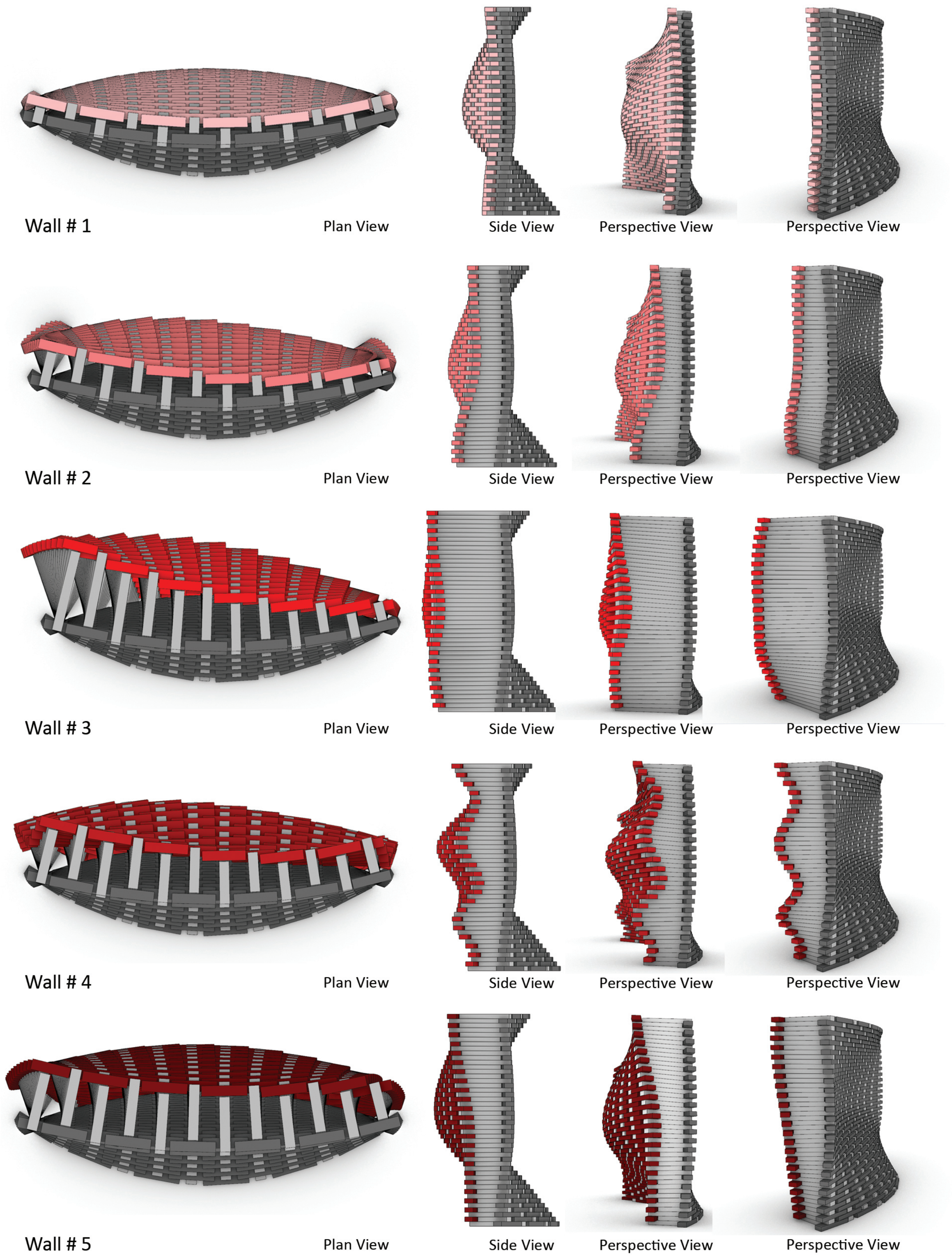
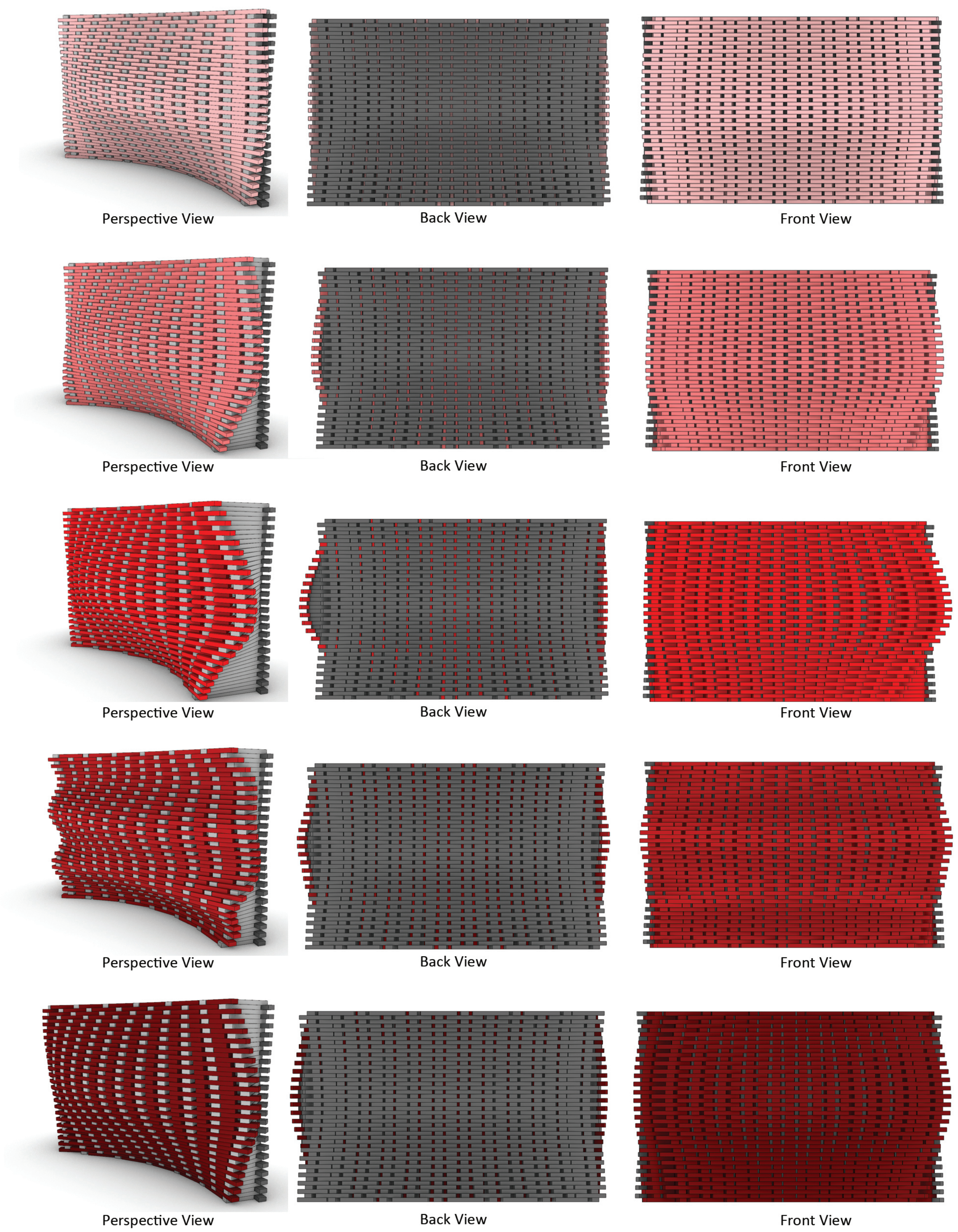


Figure 38. "T" configuration system that allows for dual-face possibility and thickness variation .



Another target is to maximize freedom in the size and shape of horizontal curvature. Freedom in horizontal curvature allows for the structure to be assembled in any shape and angle in space, for instance on the corner. In order to achieve this goal, the so-called T's head also needs to be differentiated in size, which allows the element located on the face of the structure to be coordinated according to the desired curvature size. As a consequence, this can also provide an opportunity for maintaining the smoothness of the structure's face wherever required, despite discrete elements forming the free-form curvature (Figure 41).

Gap-size variation in the system provides another possibility in terms of light control, which in turn leads to a distinctive modulation of the light coming through the structure. However, because the structure works as a double-layered system, this feature is not significant compared to the Gantenbein Vineyard Façade. This feature would be more effective by placing the elements vertically rather than horizontally, which would in turn lead to a larger gap size (Figure 39).

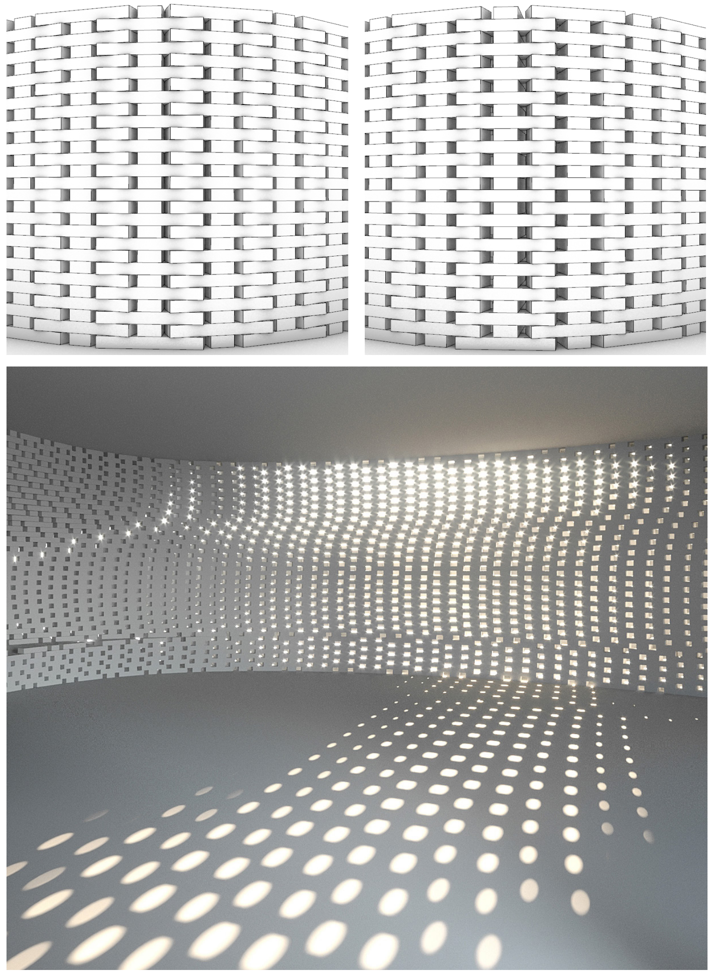


Figure 39. "T" configuration system that allows for gap variation and light modulation: (top) gap-size variation possibility; (bottom) example render of light modulation.

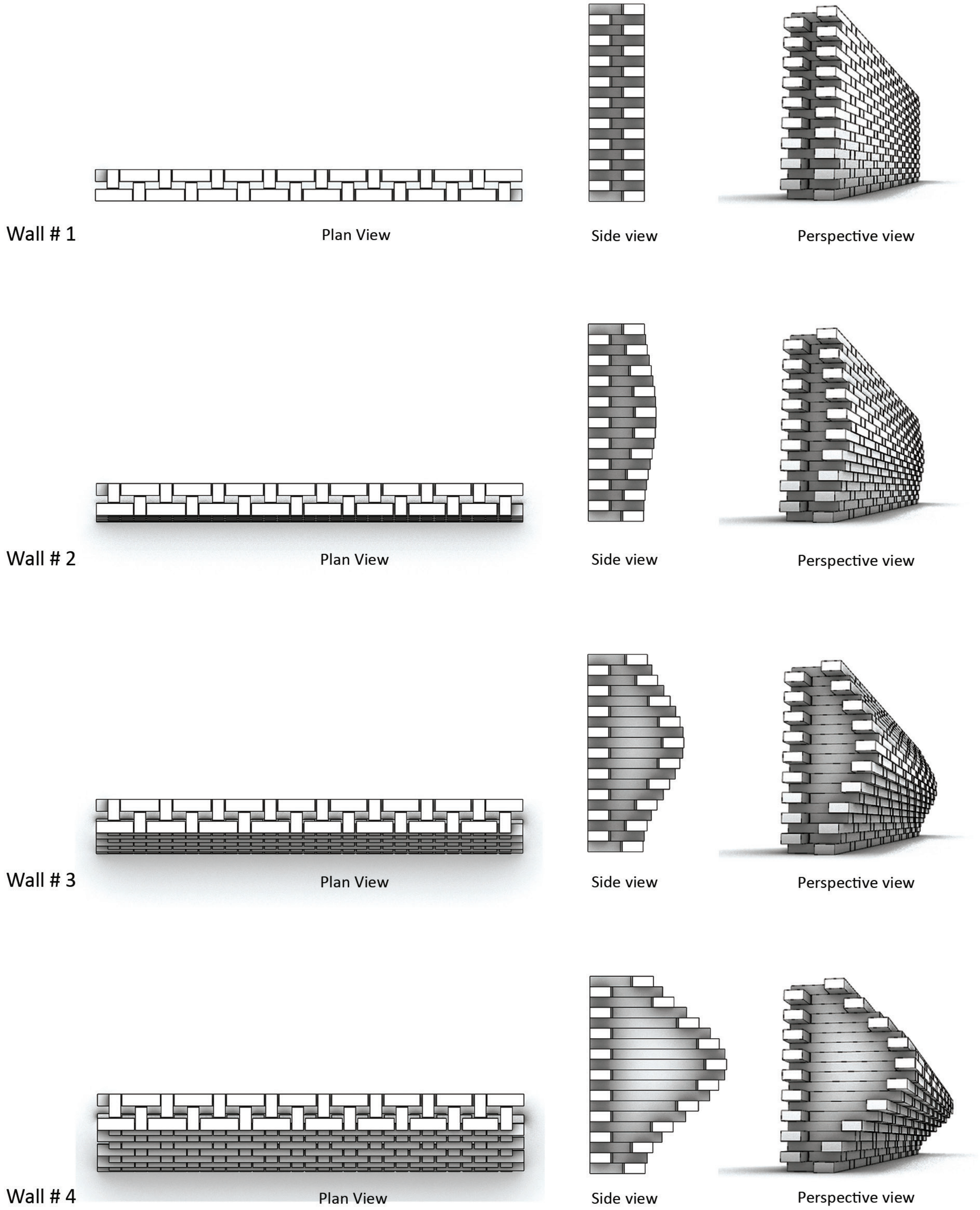
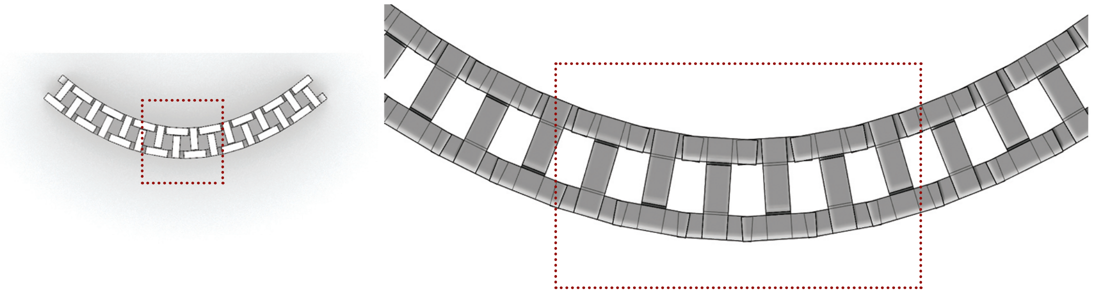
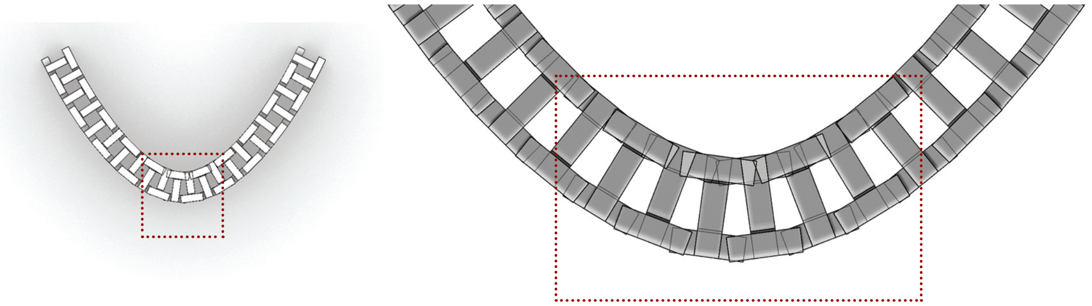


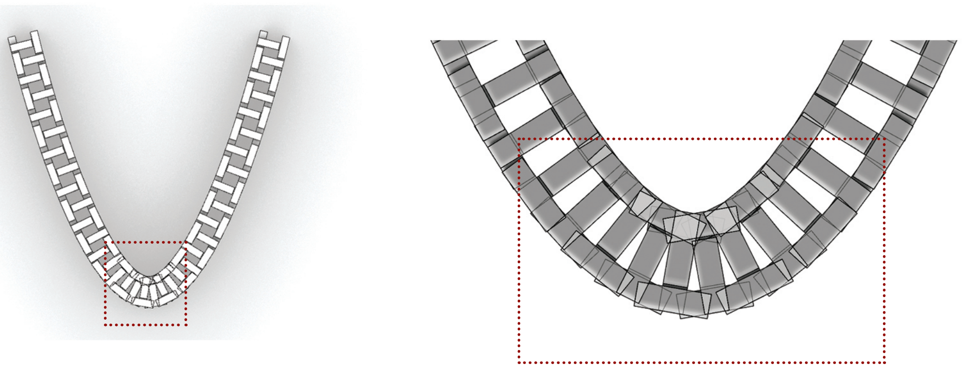
Figure 40. "T" configuration system allows for vertical curvature freedom possibility through so-called T's tail length variation.



Wall # 1 Plan View Plan View

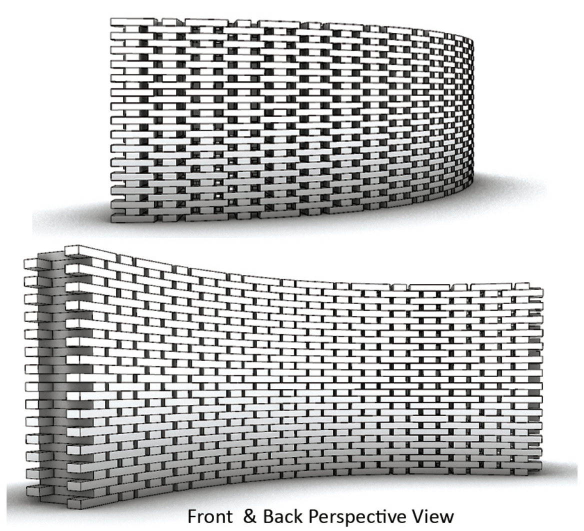


Wall # 2 Plan View Plan View

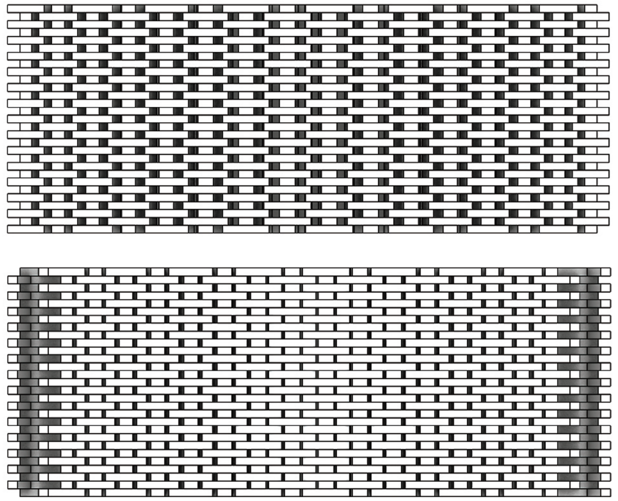


Wall # 3 Plan View Plan View

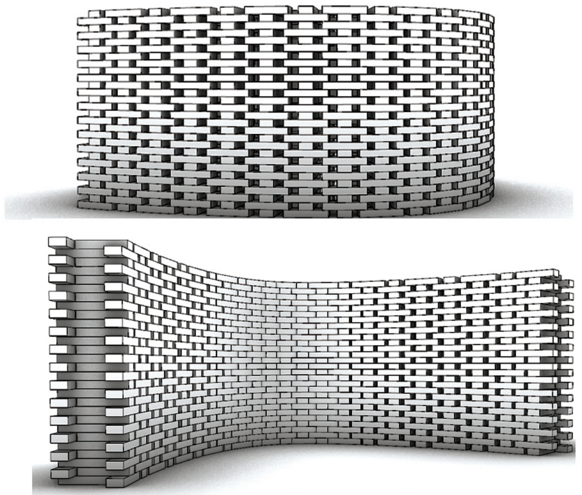
Figure 41. Horizontal curvature limitation due to so-called T's head standard size length.



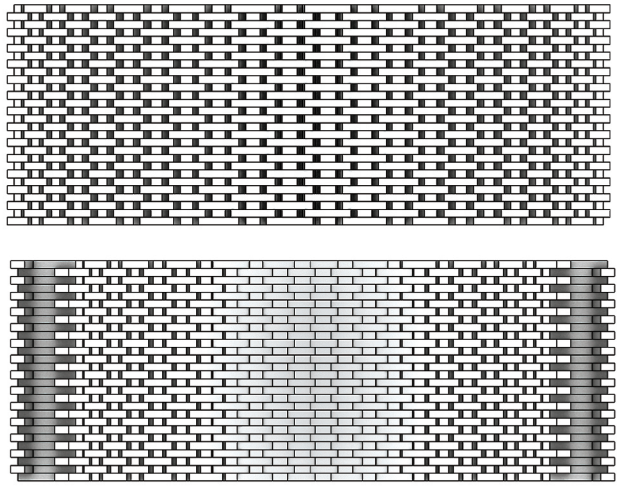
Front & Back Perspective View



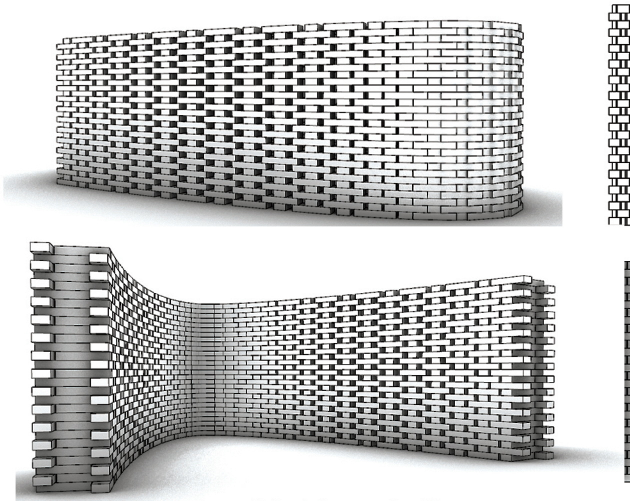
Front & Back Elevation View



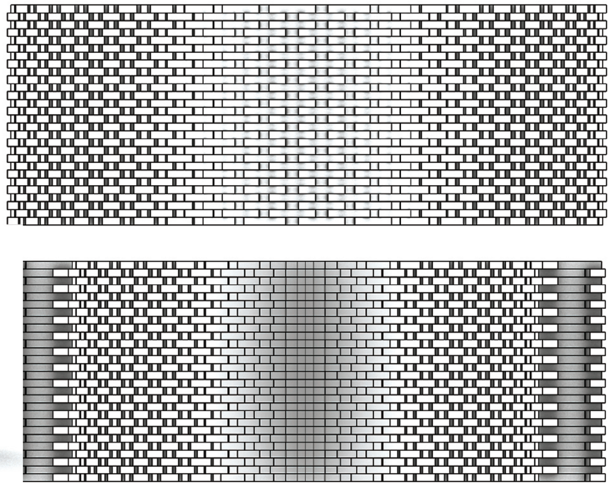
Front & Back Perspective View



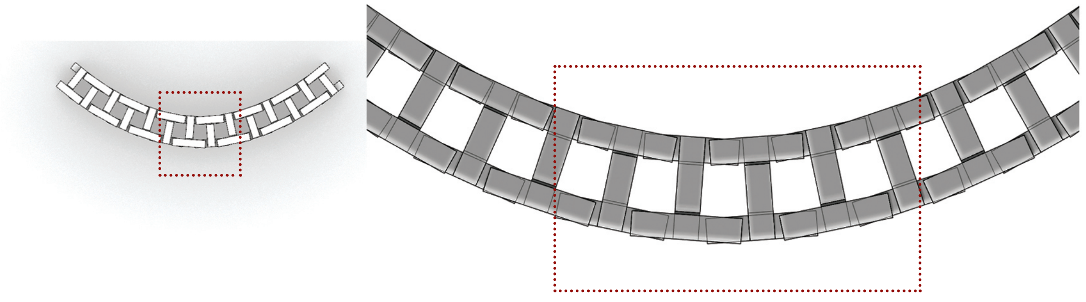
Front & Back Elevation View



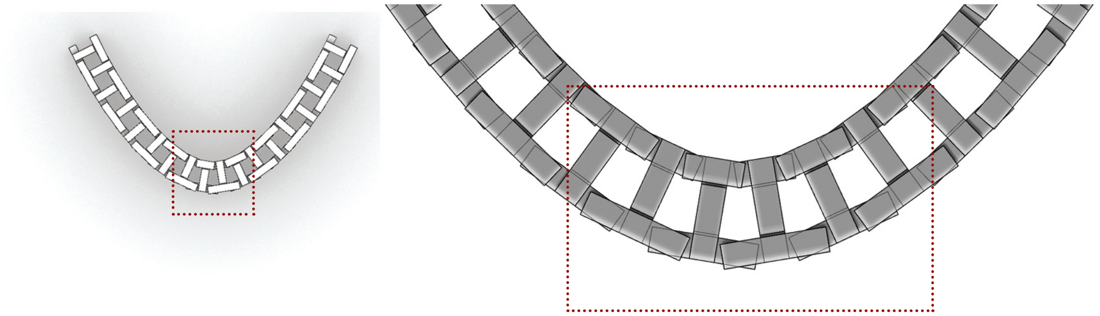
Front & Back Perspective View



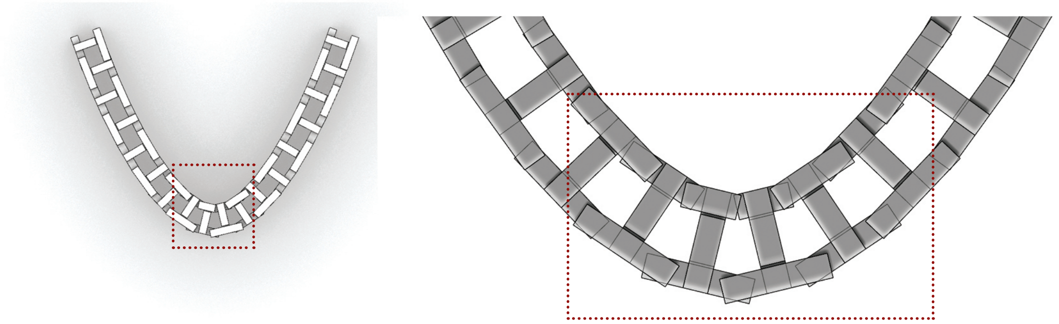
Front & Back Elevation View



Wall # 1 Plan View Plan View

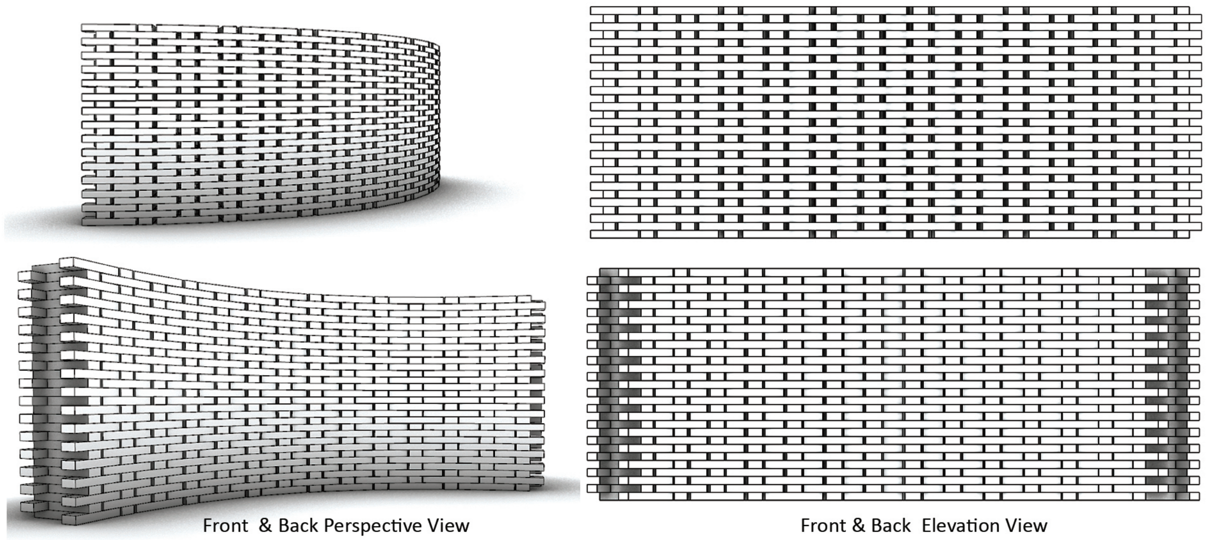


Wall # 2 Plan View Plan View

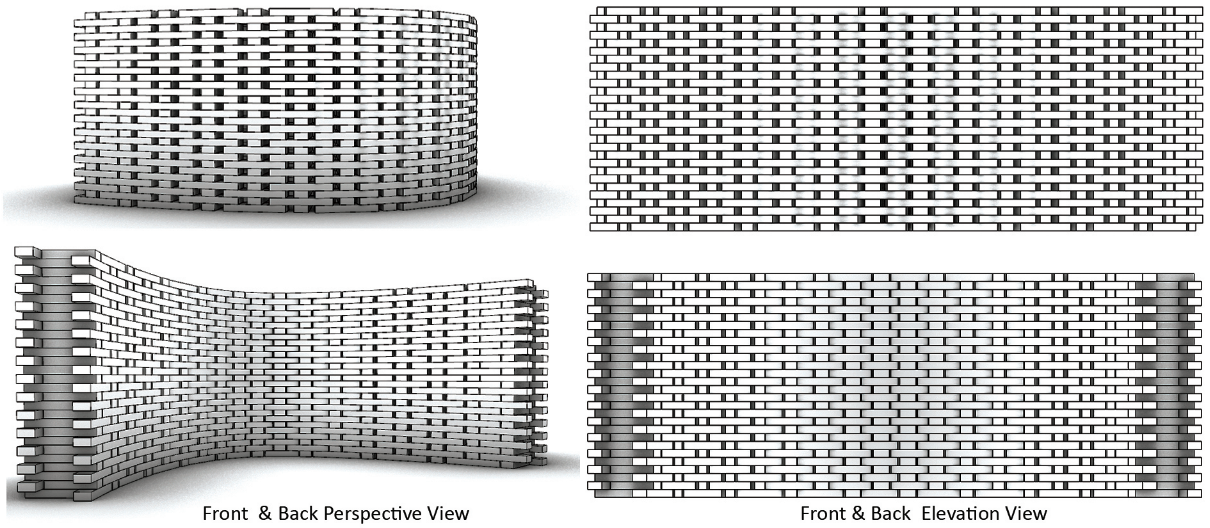


Wall # 3 Plan View Plan View

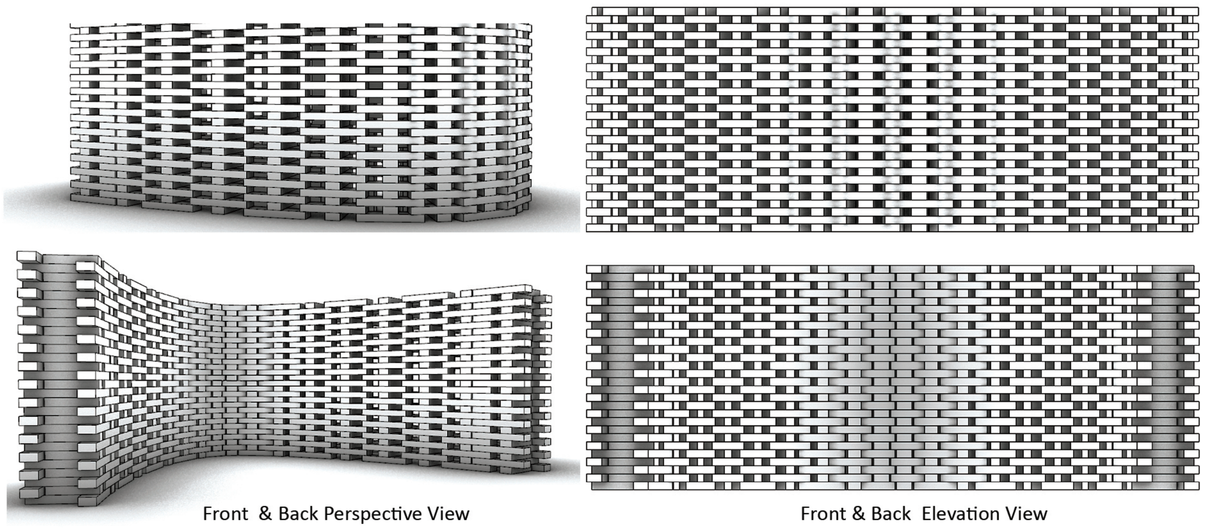
Figure 42. Horizontal curvature freedom possibility due to so-called T's head length variation.



Front & Back Perspective View Front & Back Elevation View



Front & Back Perspective View Front & Back Elevation View



Front & Back Perspective View Front & Back Elevation View

4.4.5 Digital and Computational System

In terms of digital software, Rhinoceros 3D (Rhino), with its embedded scripting language, Grasshopper, is used as a design environment for this experiment. This set-up allows a close coupling of scripting a design and its virtual representation, as well as the robotic fabrication.

The computational approach is that one double-curvature surface defines a core of the wall and two altered faces of the wall are created by using two different graph mappers through scripting, which are described more in detail in the following (Figure 44).

First of all, the core surface is divided into specific numbers through length and height. Points from the cross-section are extracted in order to create base points of the axis. Also, the vector perpendicular to the plane (Plane Normal) is found in each point. In the second step, the base points are offset a different distance on either side. To achieve different offset distances on either side, the graph mapper command, which represents a numeric mapping function, is used in order to resemble altered topologies in space. At the next stage, the axes connecting each point on the left side to its opposite on the right side are created. These axes later form the tail geometries of the T-shape in the system, which are the centre connections of both faces of the wall. As mentioned before, these connections work as a conventional stud wall. As the final step in terms of geometry design, these bases are divided into two groups that later form the two reverse T-shape geometries in the system.

Two more stages are added to the script regarding the stability control of the structure, both throughout the assembly process and in the final structure. The pivot volume control is programmed as part of the script in order to check the stability of the structure throughout the assembly process. Each time an element is added to the structure, the code control of the centre of gravity (CG) of the constructed wall is still located in the footprint of the whole structure. Therefore, the stability of the wall is controlled in order to prevent collapse during the assembly process. An error will occur in the script if there is a possibility of collapse.

In order to control the stability of the whole structure, another phase of scripting is added to the process to control the overlap of each element with the elements below it. The Gradient command is used to illustrate the errors. The overlap amounts are defined in a range of domains, and each domain is assigned to a colour, so by running the code, each element is shown in a colour in the defined range. For instance, the range of colours used in this experiment is green, yellow, and red. Green elements represent maximum overlaps; as overlap is reduced, the colour changes to yellow, then orange. However, yellow and orange elements still have acceptable overlap. Red elements do not meet the minimum overlap with elements below and thus pose a risk of collapse. In this way, the stability of the wall can be maintained as curvatures are changed in the design, and limits to both horizontal and vertical curvature size can be defined. The following figures illustrate how different curvature designs can be controlled through the script, showing different results in the stability control check (Figures 43 & 45).

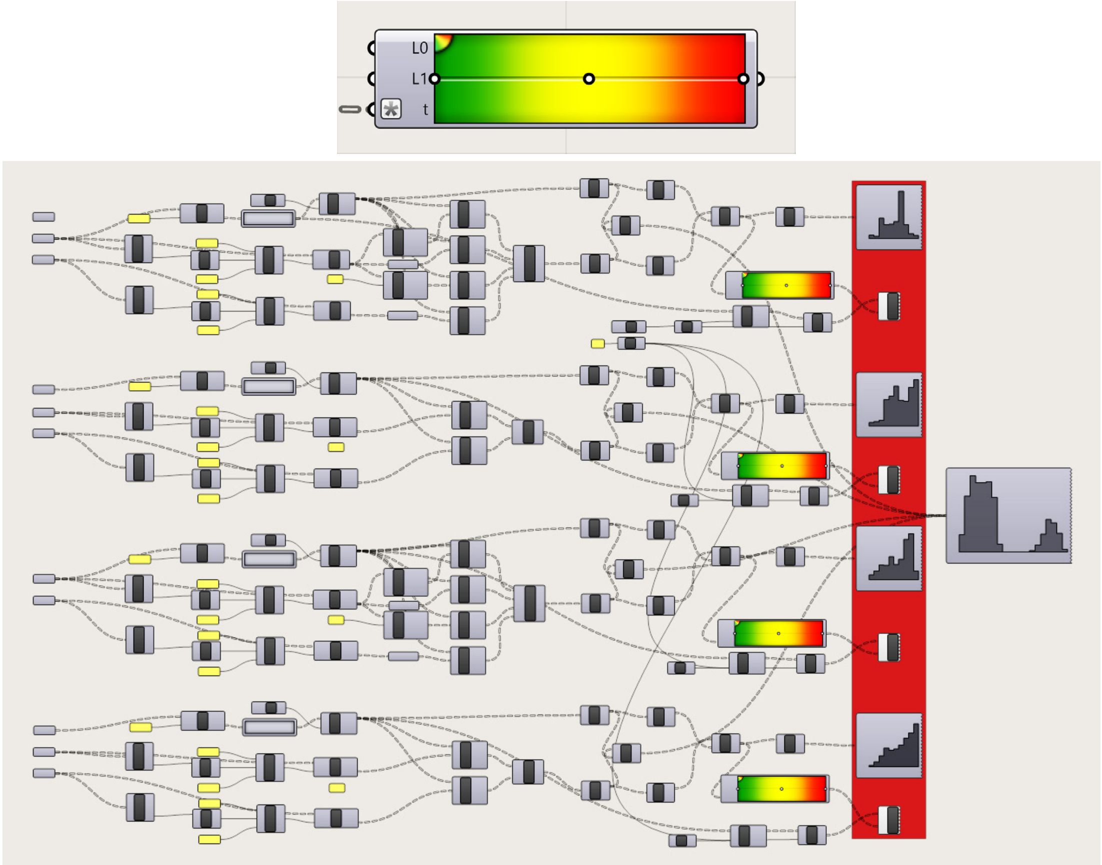


Figure 43.The script that is added to the process to control overlap areas of components in order to control the overall stability of the structure: (top) the Gradient command is used to illustrate the overlap amounts with their assigned colours.

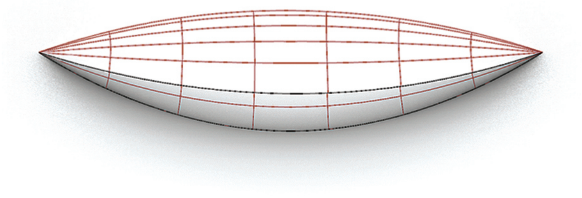
Step # 1:

The surface is considered as a core surface of the wall.

Plan View

Step # 2:

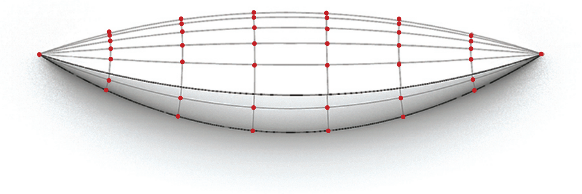
The core surface is divided into specific numbers through length and height.



Plan View

Step # 3:

Points are extracted from the cross-section of the divided surface to create base points of the axis.

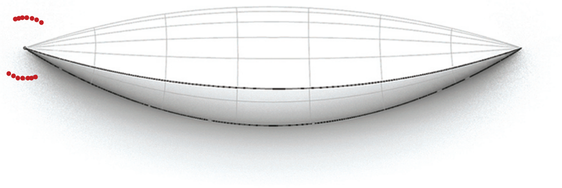


Plan View

Step # 4:

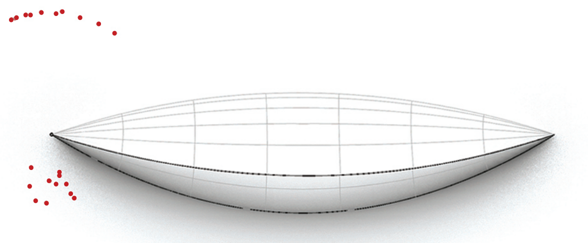
The base points of the axis are offset on either side of the core surface.

- The offset distance could be the same for all points for the same thickness of structure design.



Plan View

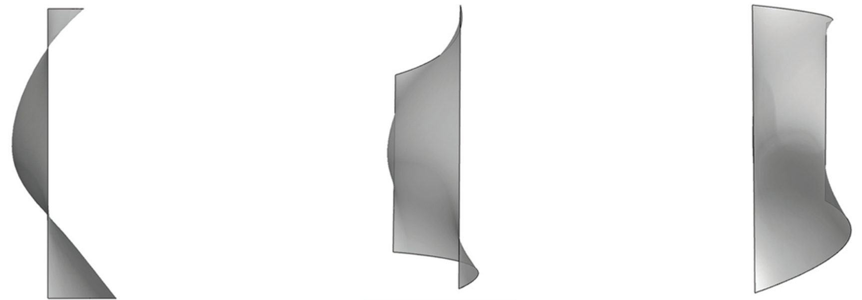
- The offset distance could be variable for each point for thickness differentiation of structure design.



Plan View

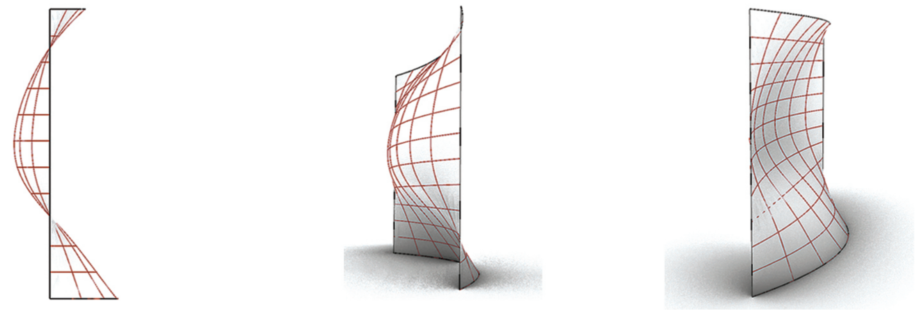
Figure 44. Computational approach steps for "T" configuration system.

Step # 1



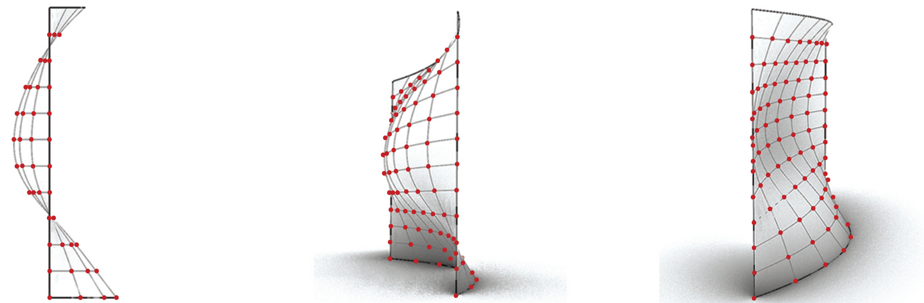
Side View Perspective View Perspective View

Step # 2



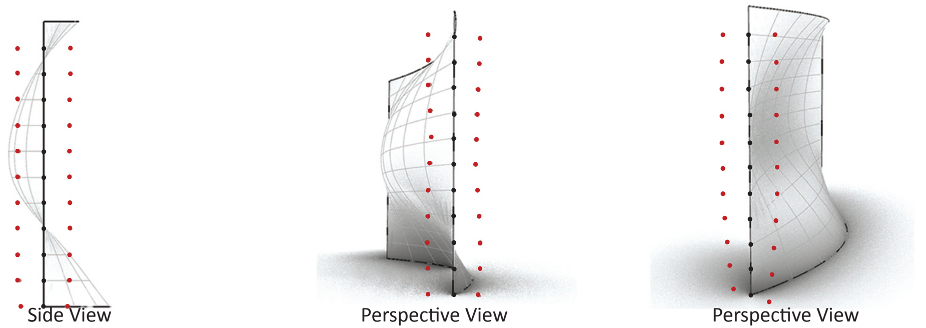
Side View Perspective View Perspective View

Step # 3

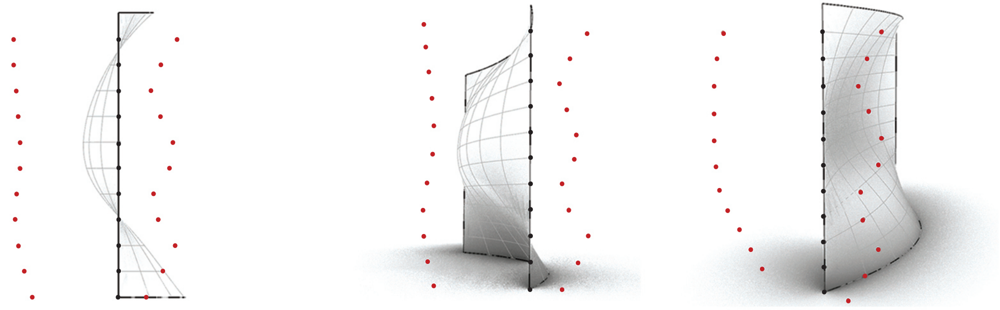


Side View Perspective View Perspective View

Step # 4



Side View Perspective View Perspective View

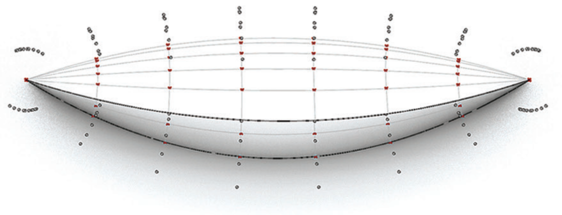


Side View Perspective View Perspective View

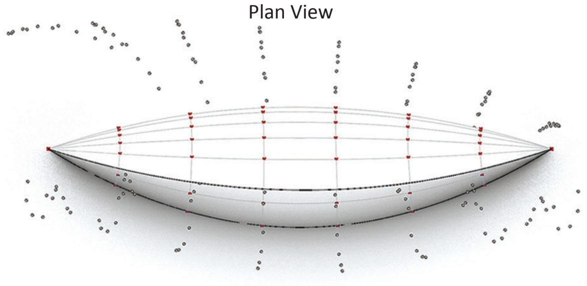
Step # 5:

The base points of the axis are offset on either side of the core surface.

- The offset distance could be the same for all points for the same thickness of structure design.



Plan View



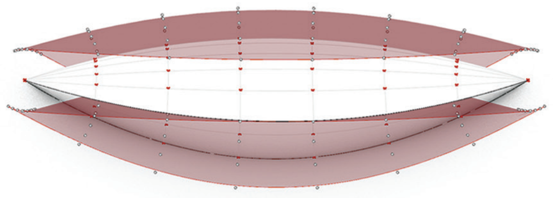
- The offset distance could be variable for each point for thickness differentiation of structure design.

Plan View

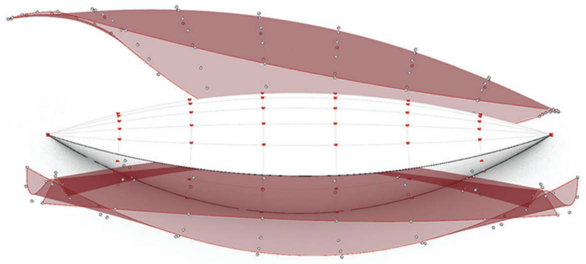
Step # 6:

The offset points on each side resemble the surface geometry of each face of the structure.

- The offset distance could be the same for all points for the same thickness of structure design.



Plan View

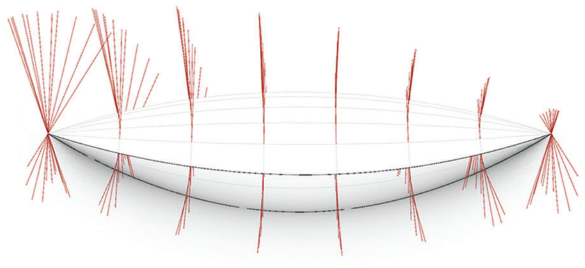


- The offset distance could be variable for each point for thickness differentiation of structure design.

Plan View

Step # 7:

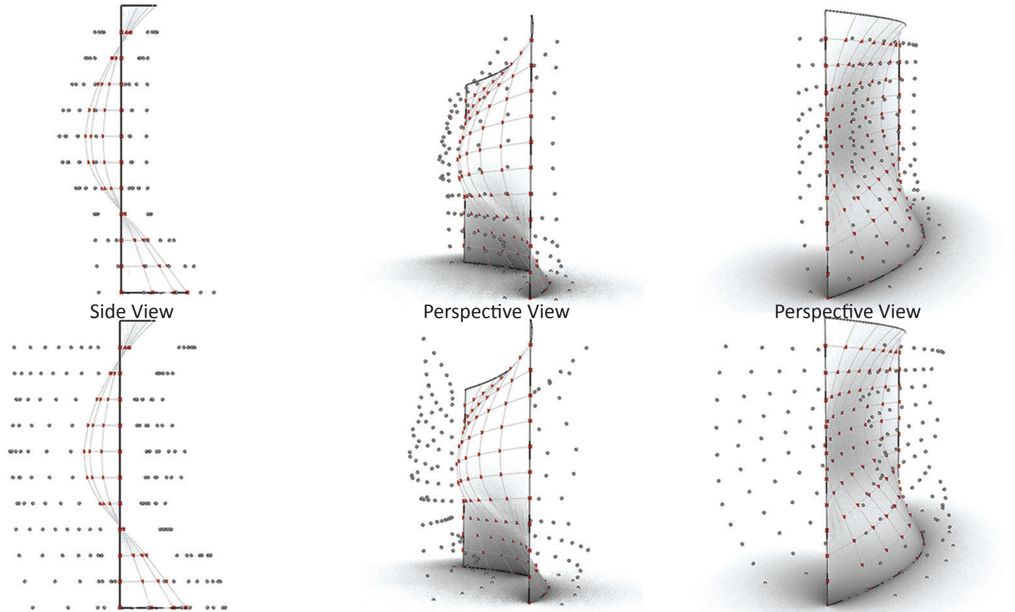
The axes that connect each point on the left side to its opposite on the right side are created. These axes later form the so-called T's tail of the "T" configuration system.



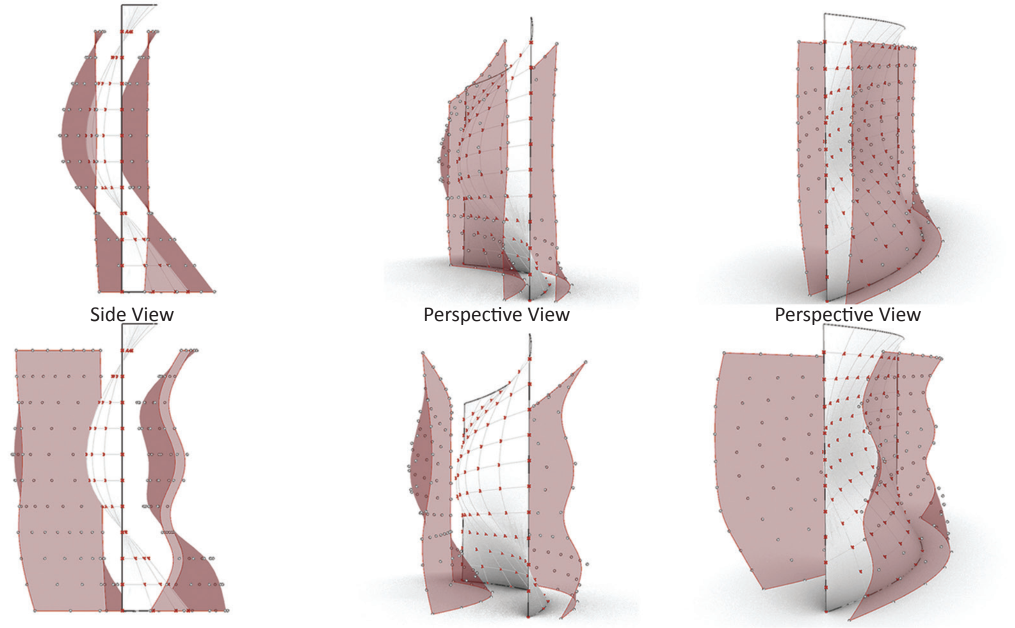
Plan View

Figure 44. Computational approach steps for "T" configuration system.

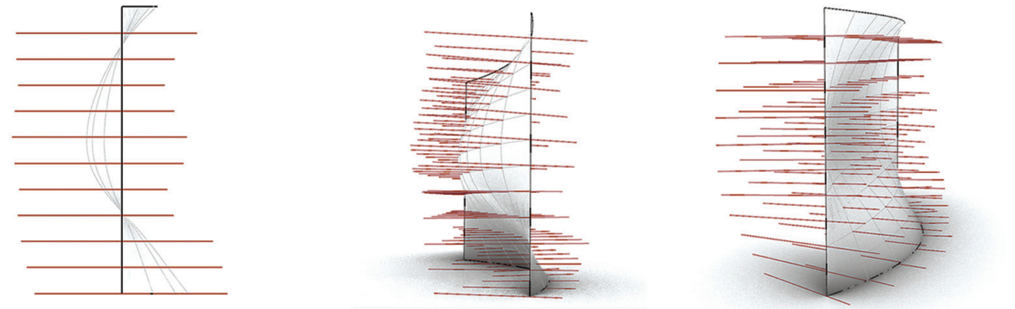
Step # 5



Step # 6

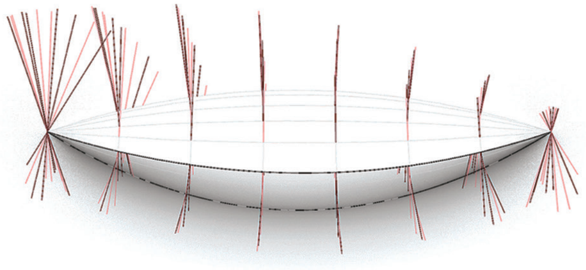


Step # 7



Step # 8:

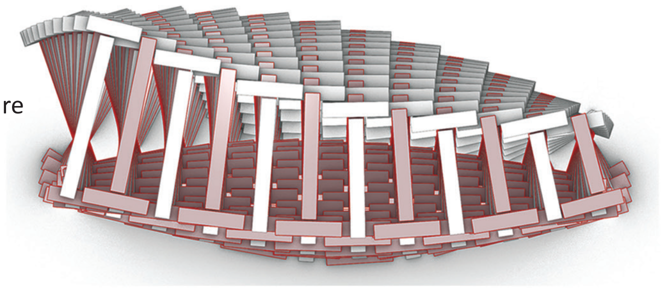
The connected axes (so-called T's tail) are divided into two groups in order to form the two reverse T-Shape geometries in the system.



Plan View

Step # 9:

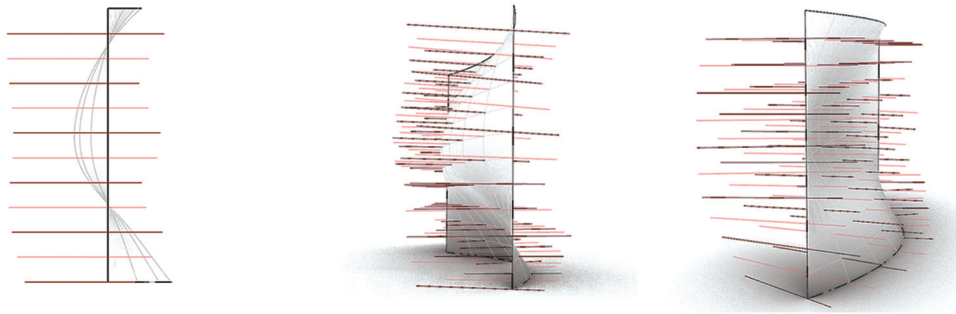
The so-called T's head are created perpendicular to the one end of the connected axes.The two reverse T-shape geometries form the module of the structure ("T" configuration system)



Plan View

Figure 44. Computational approach steps for "T" configuration system.

Step # 8

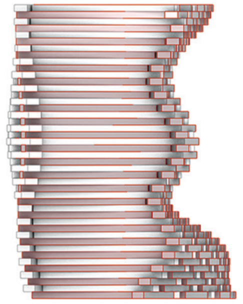


Side View

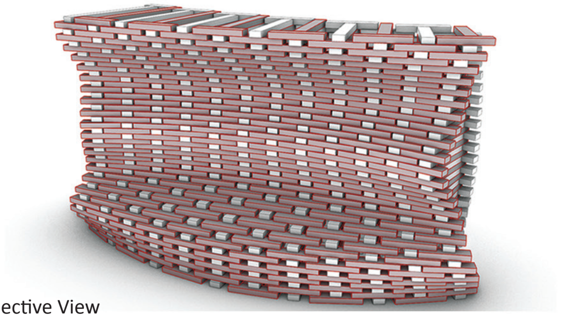
Perspective View

Perspective View

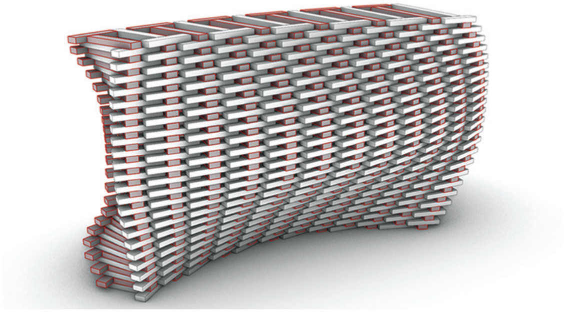
Step # 9



Side View

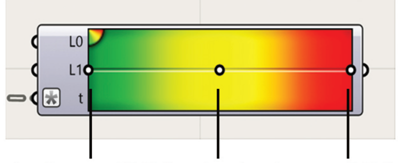


Perspective View



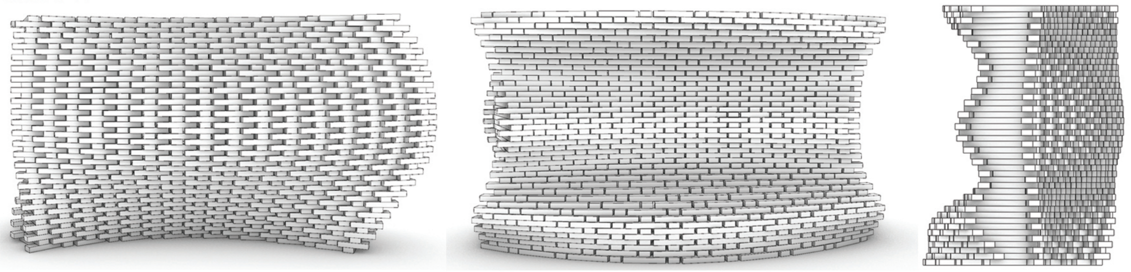
Perspective View

Gradient command illustrates overlap amounts and their assigned colours

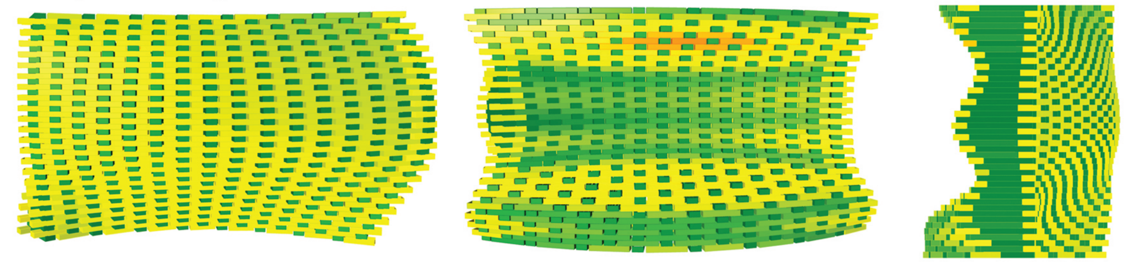


100 % Overlapping Area 50 % Overlapping Area 0 % Overlapping Area

Wall # 1

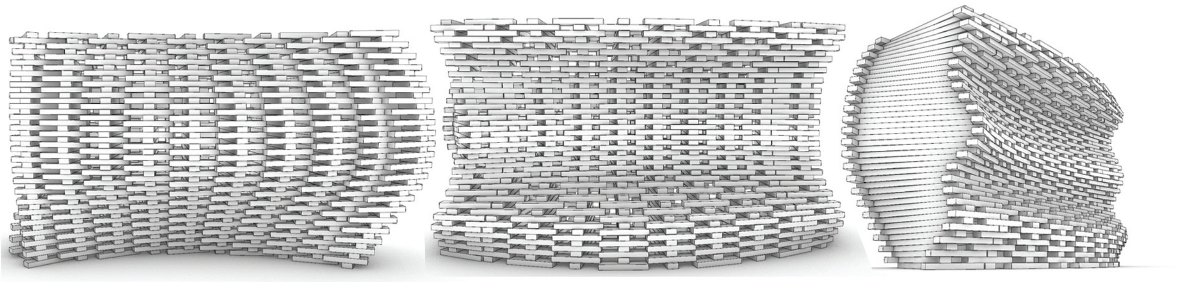


Stability Control diagram Wall # 1

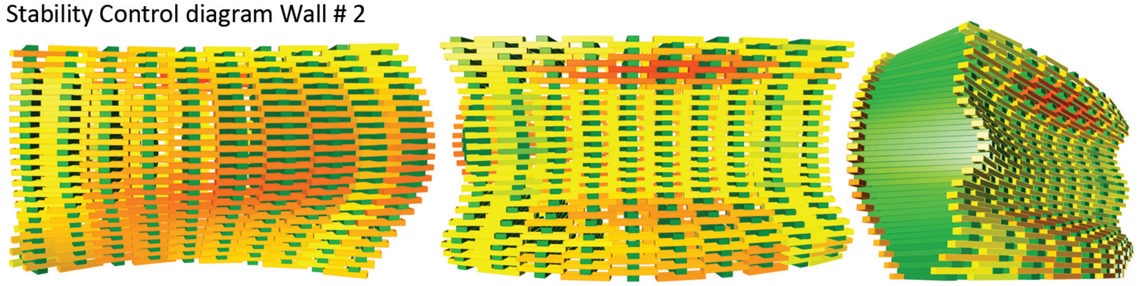


Front View Back View Side View

Wall # 2



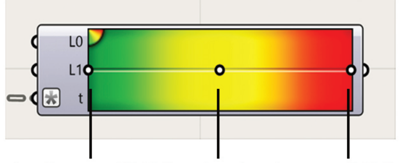
Stability Control diagram Wall # 2



Front View Back View Side View

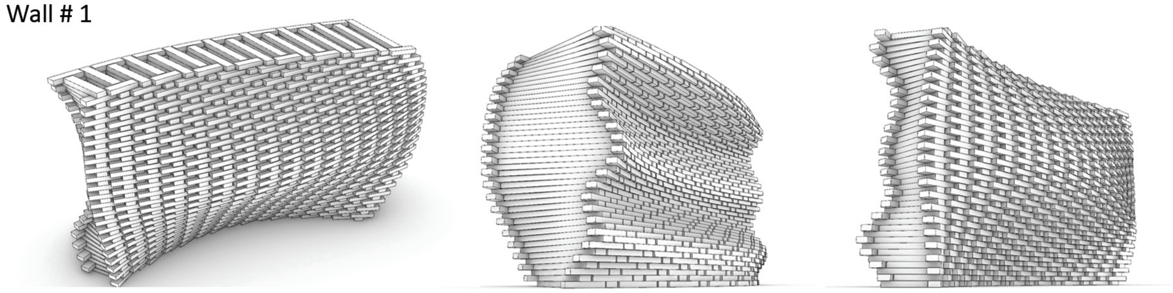
Figure 45. Computational approach in order to control the structural stability of the structure.

Gradient command illustrates overlap amounts and their assigned colours

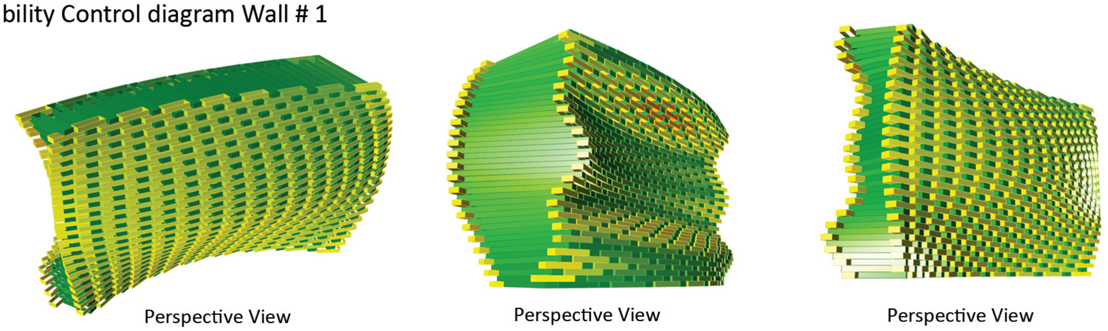


100 % Overlapping Area 50 % Overlapping Area 0 % Overlapping Area

Wall # 1

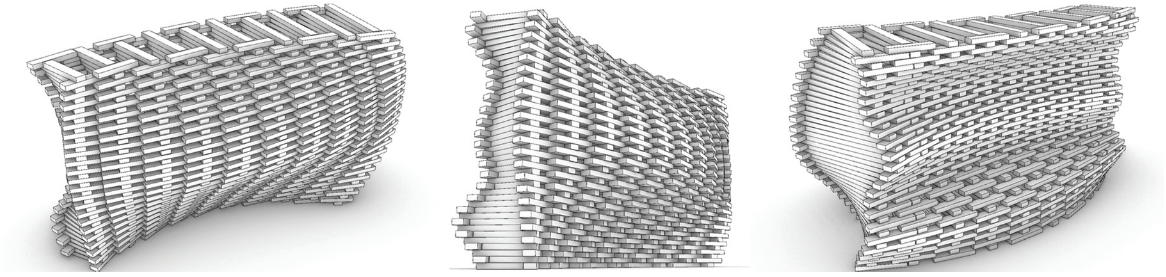


Stability Control diagram Wall # 1

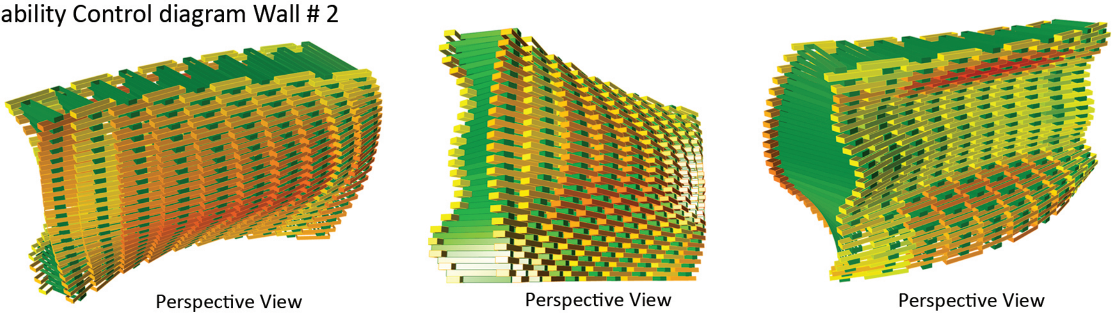


Perspective View Perspective View Perspective View

Wall # 2

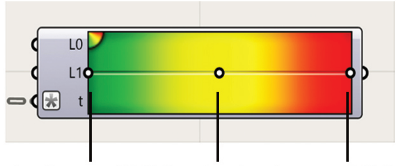


Stability Control diagram Wall # 2



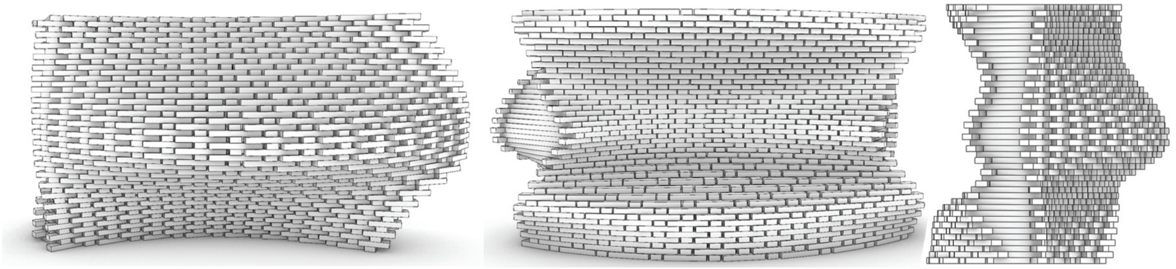
Perspective View Perspective View Perspective View

Gradient command illustrates overlap amounts and their assigned colours

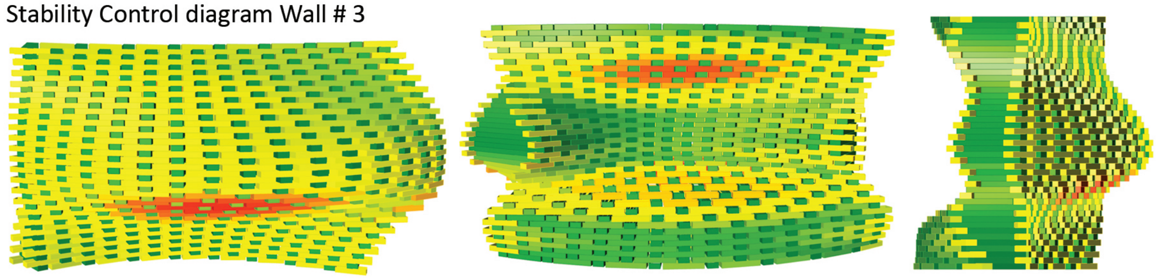


100 % Overlapping Area 50 % Overlapping Area 0 % Overlapping Area

Wall # 3



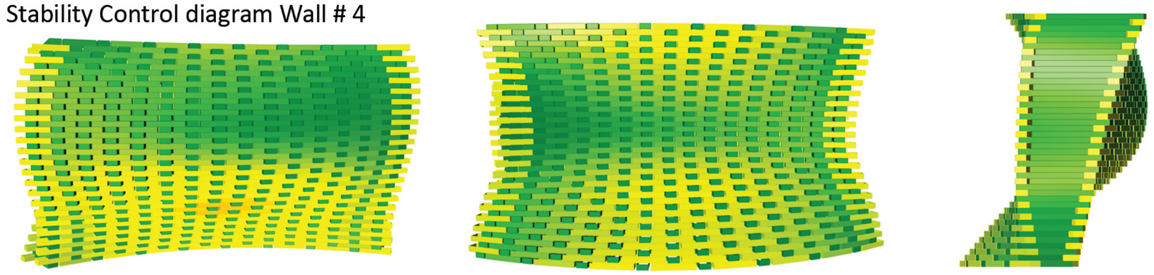
Stability Control diagram Wall # 3



Front View Back View Side View

Wall # 4

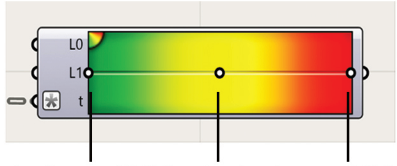
Stability Control diagram Wall # 4



Front View Back View Side View

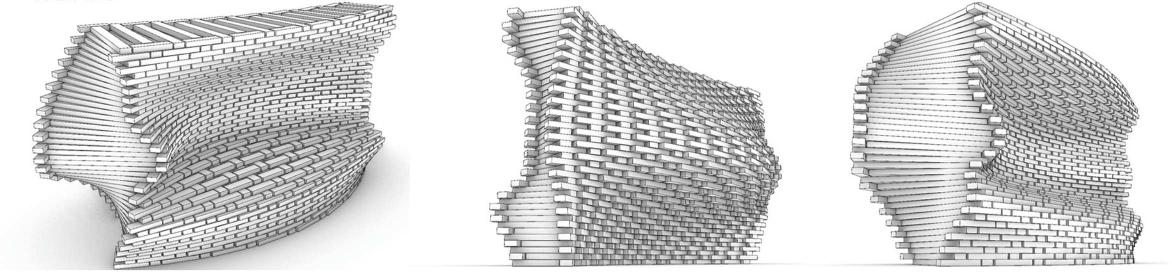
Figure 45. Computational approach in order to control the structural stability of the structure.

Gradient command illustrates overlap amounts and their assigned colours

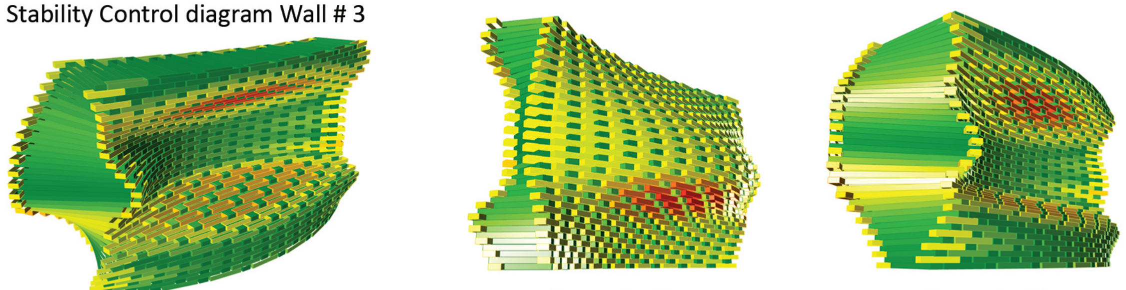


100 % Overlapping Area 50 % Overlapping Area 0 % Overlapping Area

Wall # 3

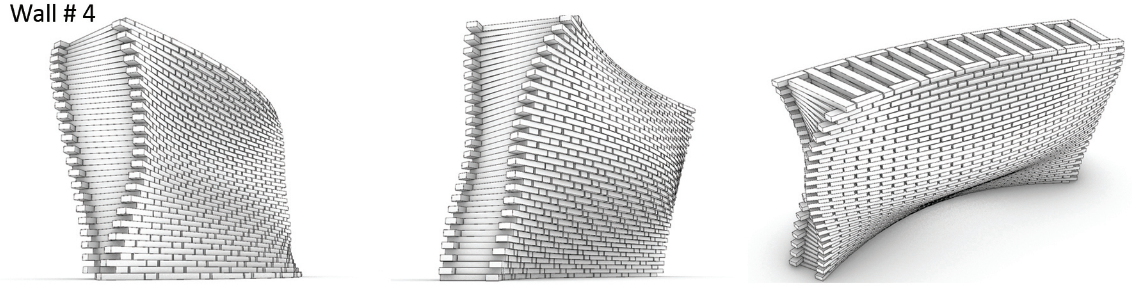


Stability Control diagram Wall # 3

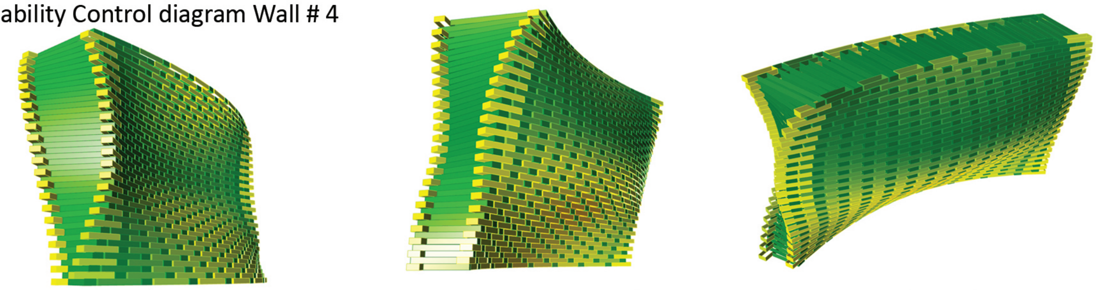


Perspective View Perspective View Perspective View

Wall # 4



Stability Control diagram Wall # 4



Perspective View Perspective View Perspective View

4.4.6 Pre-fabrication Possibility

While the final prototype does not address this aspect directly, careful consideration was given to the feasibility of prefabrication of the system in the robotic shop, preparation for transportation and installation on site. The prefabrication concept is of important consideration for the following reasons:

- Safety and quality control: robots work better and more safely in a protected environment.
- Efficiency: fabrication shops work 24/7, which is more productive than on-site fabrication. On-site installation increases construction time management.
- Human errors: human labour plays a lesser role in the shop, keeping errors to a minimum.
- Waste reduction: factory production minimizes material wastage.
- Cost: the project will be more economical for the above reasons.

Therefore, exploring prefabrication for the design system is of interest. The investigation is divided into two main criteria: the panel geometry system and the panel connection strategy. Both subjects are described in more detail below.

4.4.6.1 Panel Geometry System

In this section, different geometry approaches are investigated. The potentials and limitations of each approach are described and illustrated through diagrams.

Approach 1

For the first approach, the wall is divided into a square-grid system. The vertical joints in this system are considered weak points in the wall that can affect its whole consistency and integrity, and in turn reduce its overall stability. Although modifying the stacked grid system into a staggered system can improve it, the joints would still be the weak point of the structure. Moreover, the square-shaped panel should be connected vertically to those beside it and horizontally to those below it. Connecting the toothed-shaped vertical sides of the panels would, however, pose a significant challenge for on-site installation (Figure 46).

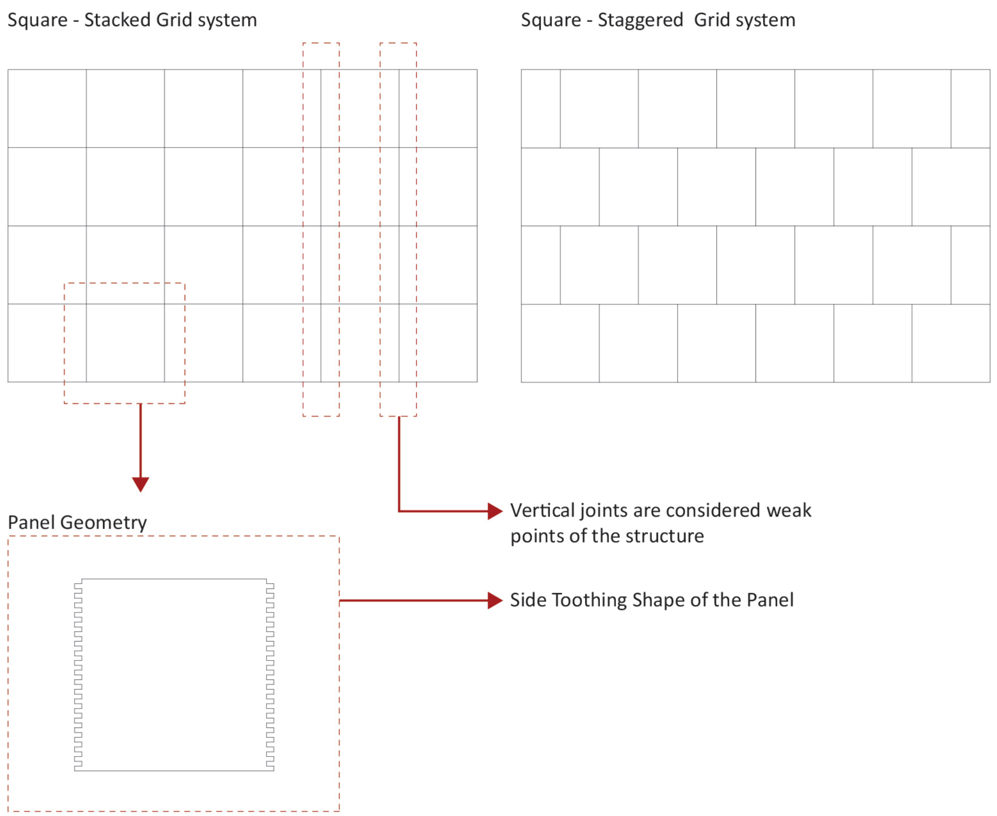


Figure 46. Approach #1, grid system and panel geometry of pre-fabricated structure for the "T" configuration system.

Approach 2

In the second approach, the triangular network is considered as a grid system. This triangular system addresses the above-named issues of the square-grid system. First, the potential weak axis of the square grid is no longer a problem in the diagrid form of the triangular network. Moreover, the stepped bonding arrangement on the sides of each panel provide a feasible form for on-site installation. The proposed installation technique involves first placing the panels that point up, then placing the ones that point down. However, this triangular grid network raises a new problem. The complex geometry of the double-curvature wall requires a predefined strategy in the installation process regarding the correct position of each panel in relation to the ones to which it will be connected (the connection method will be described in detail in section 4.4.6.2). The problem originates in the installation of the first layer, in which all panels pointing up must be precisely placed next to each other with no connection or overlap. In this situation, there is no strategy available to determine the panels' locations. As a result, the base element, which is the connection between the wall and the foundation, must be prepared in the shop with regard to the location of panels that are prefabricated on it. Another criticism of the triangular panel system is that the triangular shape is not suitable for a modular system because the corners of the panels are fragile; as a consequence, they are not appropriate for prefabrication and transportation (Figure 47).

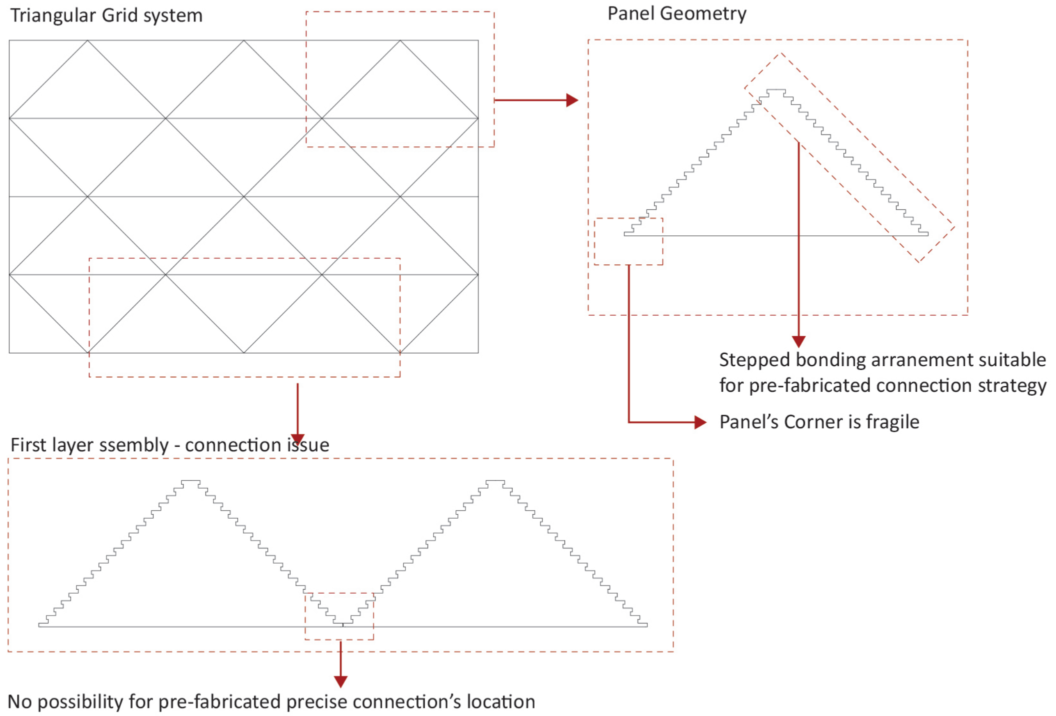


Figure 47. Approach #2, grid system and panel geometry of pre-fabricated structure for the "T" configuration system.

Approach 3

The third approach is to investigate an oblique pattern. As the potential weak axis of the square-grid system is removed, this pattern benefits from the step-bonding arrangement on the sides of the panels for connecting them. Moreover, it addresses the installation issue and fragile shape of the panels discussed in approach 2. The panels can be installed exactly next to each other on each layer (Figure 48).

Although three approaches are explored here, there are potentially many more that could be investigated. However, approach 3 illustrates that the oblique pattern can meet the requirements of all fabrication, transportation, and installation processes (Figure 48).

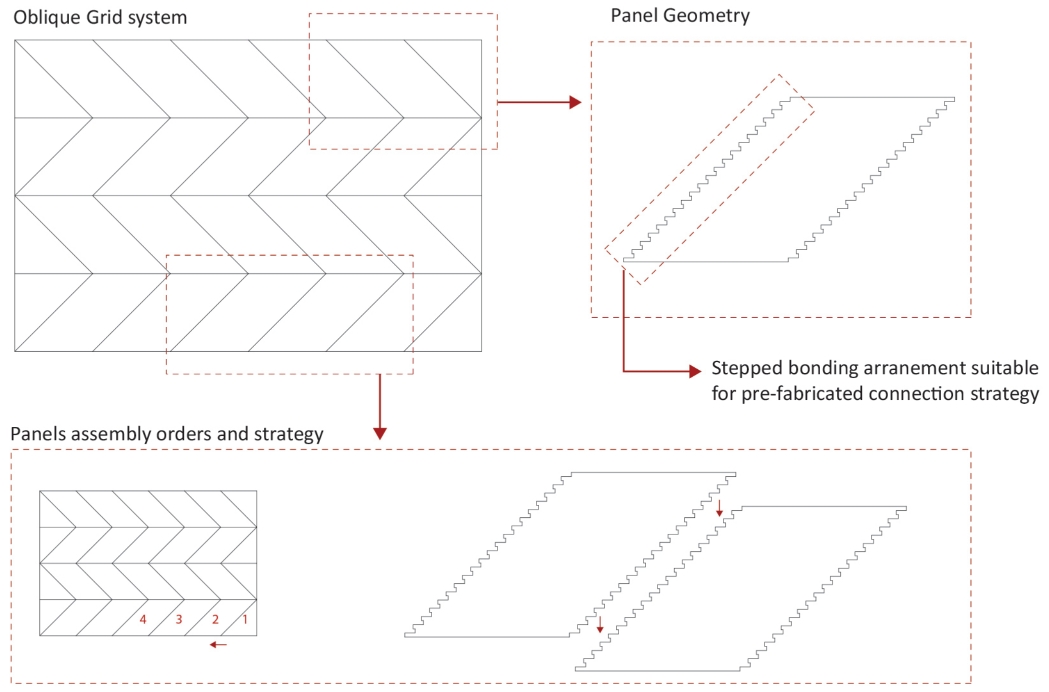


Figure 48. Approach #3, grid system and panel geometry of pre-fabricated structure for the "T" configuration system.

4.4.6.2 Panel Connection Strategy

A dowel-type timber connection is proposed as the joint for the panel connection system. Wooden dowels have been used in manufacturing and woodworking for many centuries. Much research has been conducted on the load-carrying behaviour of these connections, although this is not the focus of this section. Therefore, wooden dowel is considered as the first choice. However, steel dowel pins and screws can also be used to address structural requirements, and wherever shear reinforcement is of importance. The required length and diameter of dowels can also be determined according to the structural situation, which in turn can be analyzed and designed for each specific joint. These parameters can later be added to the design and fabrication script.

The idea of a dowel with a corresponding hole is chosen due to its suitability for prefabrication. This connection strategy is not only very efficient in the installation process, it is very appropriate for robotic fabrication. Typical drilling and milling operations can be added as part of the fabrication process (either manual or automated options). The predefined, corresponding holes are drilled in their exact location on elements that will be located on the outer layers of each panel. As a result, throughout the installation process, panels will be connected at the exact angle and location with regards to the predefined joints.

It should be noted that in a dowel-type connection, if dowels are glued into blind holes (i.e. dowel-based joinery), detailed consideration should be given for relieving the hydraulic pressure of air and glue in the process, which is not a focus in this project.

While a prefabrication strategy can lead to a more efficient, economical, and higher-quality result in the construction industry, for this project, in particular, there are other aspects that are taken into account. It provides possibilities for the structure to be manufactured at various scales and in diverse locations. Although on-site robotic fabrication has become the centre of attention in recent years, the robot's inherent place in the factory and progress in this context mean that prefabrication and on-site installation is the safer and more rational solution. Therefore, exploring the prefabrication potential of the system is of significance and can be seen as the essential feature of this robotic fabrication design project.

5.FABRICATION: ROBOTIC ASSEMBLY OF TIMBER STRUCTURES THROUGH STANDARD & NON-STANDARD COMPONENTS

5.1 Objective of Experiments

The objective of the two experiments in this thesis was to develop and validate a robotic-based production method for a timber structure through standard and non-standard components. The experiments identified particular designs with a specific stacking system that incorporates the essential criteria and parameters of an automated assembly process. In both experiments, the physical prototype tests expressed the concept of the approach, aspects of design, and the manufacturing process of each investigation. For each test, the fabrication process was developed based on the results of the experiment.

In both experiments, similar to the assembly process for some of the brickwork projects at ETH Zurich, the degree of automation of the robotic assembly process was low. The robot was used where its digital controls became vital for applying the wall design.[182] Digital control of the robot was used in positioning the individual components in their precise locations, which could be considered the main purpose of robotic fabrication in architecture.[183] Ultimately, however, all steps of fabrication could be converted to fully automated processes, given speed optimization, in order to be applied in the building industry.

For Experiment 1, robotic assembly of standard components was applied to an architectural element, a wall. For the Experiment 2, robotic assembly of non-standard (minimal customization of standard) components was applied to a furniture element, a bench. For both experiments, timber slat – a small profile of dimensional lumber – was used as a generic material to more closely approximate real-world demands in terms of materiality.

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[182] Bonwetsch, "Robotically assembled brickwork."

[183] Bonwetsch, "Robotically assembled brickwork."

5.2 Fundamental Parameters of the Robotic Assembly Process (Experiment 1 and Experiment 2)

5.2.1 Mechanical Tooling, Robotic Set-Up and Assembly Process

Both physical experiments were conducted in the digital fabrication lab at the School of Architecture, University of Waterloo. The UR10 (Universal Robot), a six-axis industrial robot with a reach of 1300 mm and a payload of 10 kg, was mounted on a table for the experiments. The robot's reach and spatial layout set the physical boundaries of the design space and assembly process. The robot was equipped with the two-finger adaptive gripper (2F-85). It should be noted that, since every alteration of the robot's set-up has a direct influence on the overall process, the external two-finger gripper was incorporated in the first step of the design-fabrication process (Figure 49).

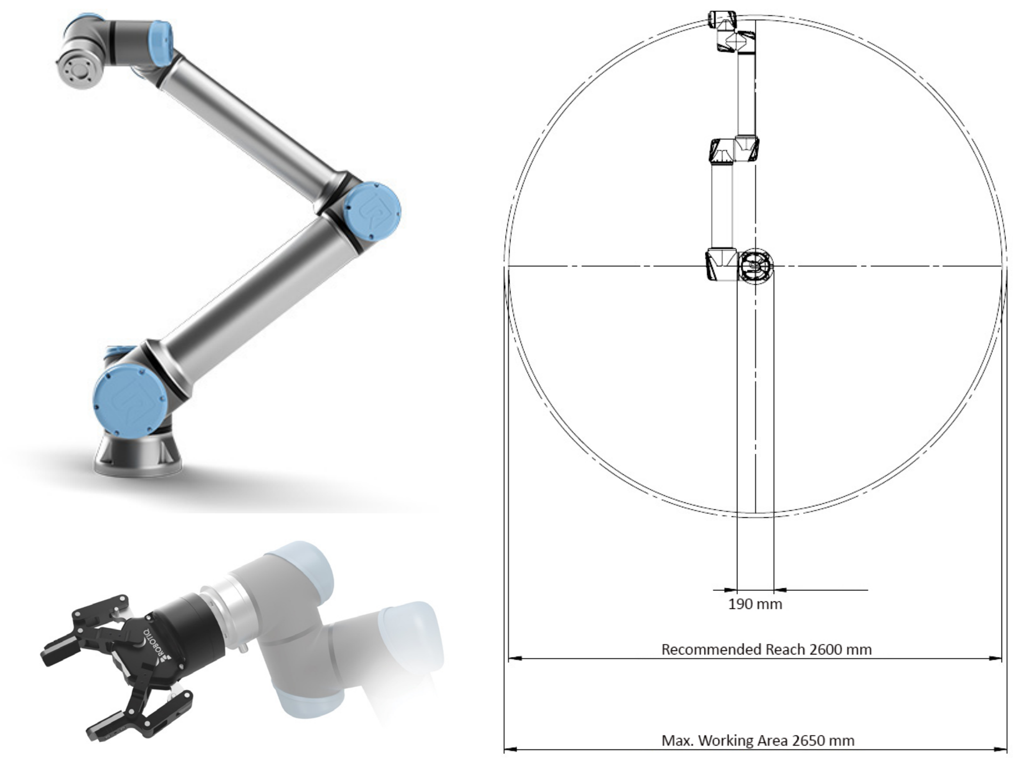

Figure 49. UR10 Universal Robot; (top left) UR10; (right) UR10 reach access, plan view; (bottom) 2F-85, two-finger adaptive gripper.

The following diagrams depict the general process and robotic set-up used for the robotic assembly of the experiments that followed.[184] This general process will be explained in more detail in the descriptions of the two separate experiments below (Figure 50).

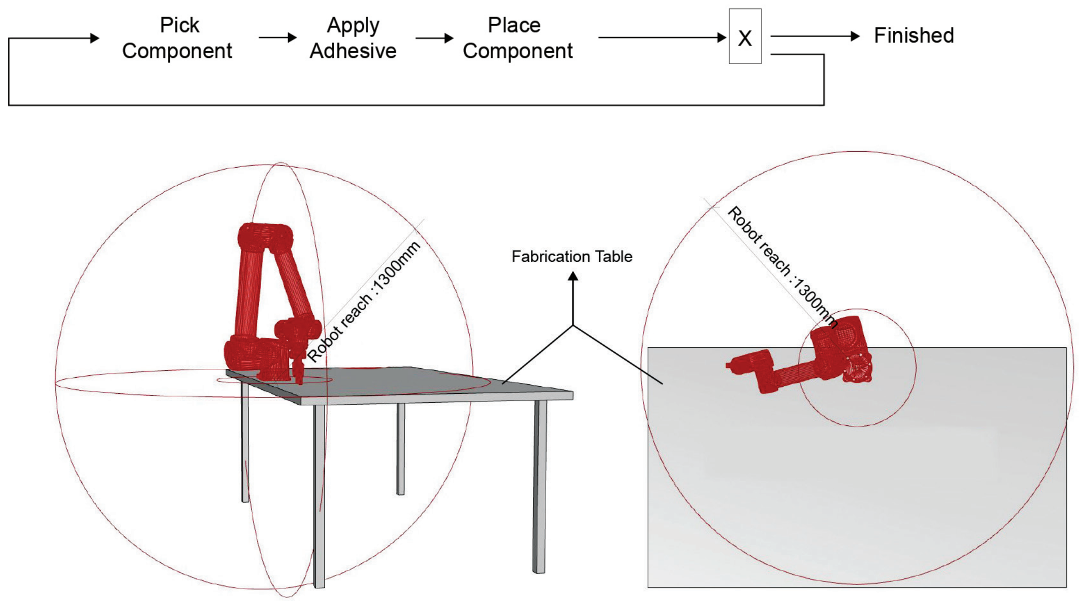

Figure 50. (Top) general process of assembly fabrication; (bottom) general robotic set-up of experiments.

5.2.2 Robotic Control

The steps required to assemble a structure using differentiated components needed to be translated into a control code for the robot to execute. The main control program was generated automatically from the design data within the Rhino and Grasshopper design environment, and the position and spatial orientation of each component of the wall was translated into control commands for the robot. Scorpion, an open source plugin, was used to control and manipulate Universal Robots from the toolpath within Rhino Grasshopper. The opening and closing of the gripper was added as a readable syntax within the program loop in a determinate sequence of steps. The final script, describing the complete sequential assembly process, was extracted and used to run and control the robot (Figure 51).

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[184] Bonwetsch, "Robotically Assembled Brickwork."

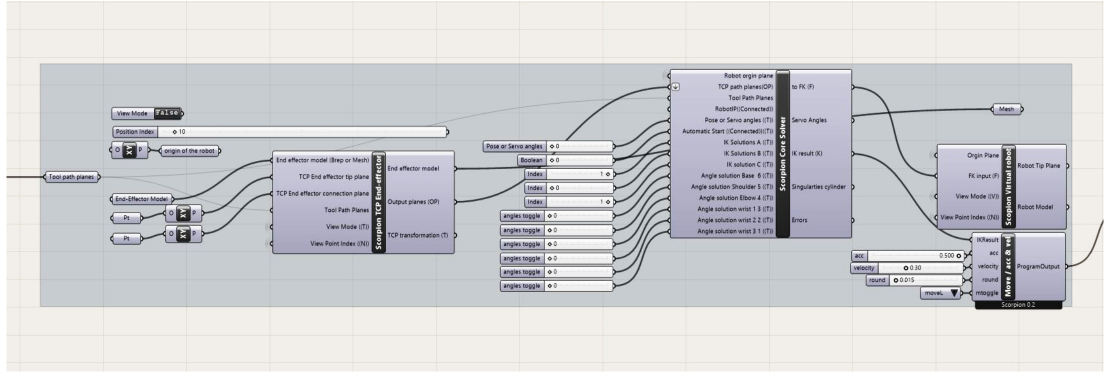

Figure 51.Scorpion Plugin that is used to control UR10 from the toolpath within Rhino Grasshopper.

5.2.3 Material System

Following the main concept of this research – using the robot's ability to individually control a large number of generic elements – timber slat, a small profile of dimensional lumber, was chosen due to its simplicity and workability. The 1" x 2" x 8' lumber (17 x 37 x 2438 mm), available commercially, was adopted as the material of choice for both experiments. For the Experiment 1, "robotic assembly of a structurally informed wall system using standard components," the wood slat was cut in advance into 6" (152 mm) lengths ready for assembly by the robot as a standard-sized component. For the Experiment 2, "tête-à-tête: adaptive fabrication method for robotic stacking with non-standard components," the wood slat was cut into 2' (610 mm) lengths to use as feeding material to the robot, ready to be cut to various lengths throughout the fabrication process. Each experiment will be described in more detail below.

A woodworking adhesive, Pro Carpenters Glue, with a cure time of twenty-five minutes, was chosen as the bonding material.

5.3 Experiment 1: Robotic Assembly of a Structurally Informed Wall System Using Standard Components

5.3.1 Design

The first experiment investigated the design implications of a robotic assembly process of the "T" configuration system in a free-form wall structure through standard components. A double-curvature geometry wall of 1400 mm in length and 2000 mm in height was designed. Due to limitations of the robot's reach, it was decided that the wall's length should be designed within the possible reach of the robot's arm. In terms of height, the wall was divided into five sections that were assembled together later (Figure 52).

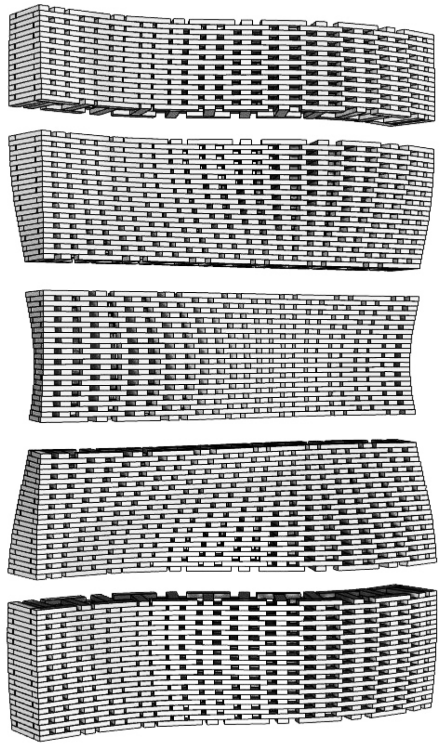

Figure 52. The proposed wall is divided into five sections.

The following drawing illustrates the final design proposed for the Experiment 1 prototype (Figure 53).

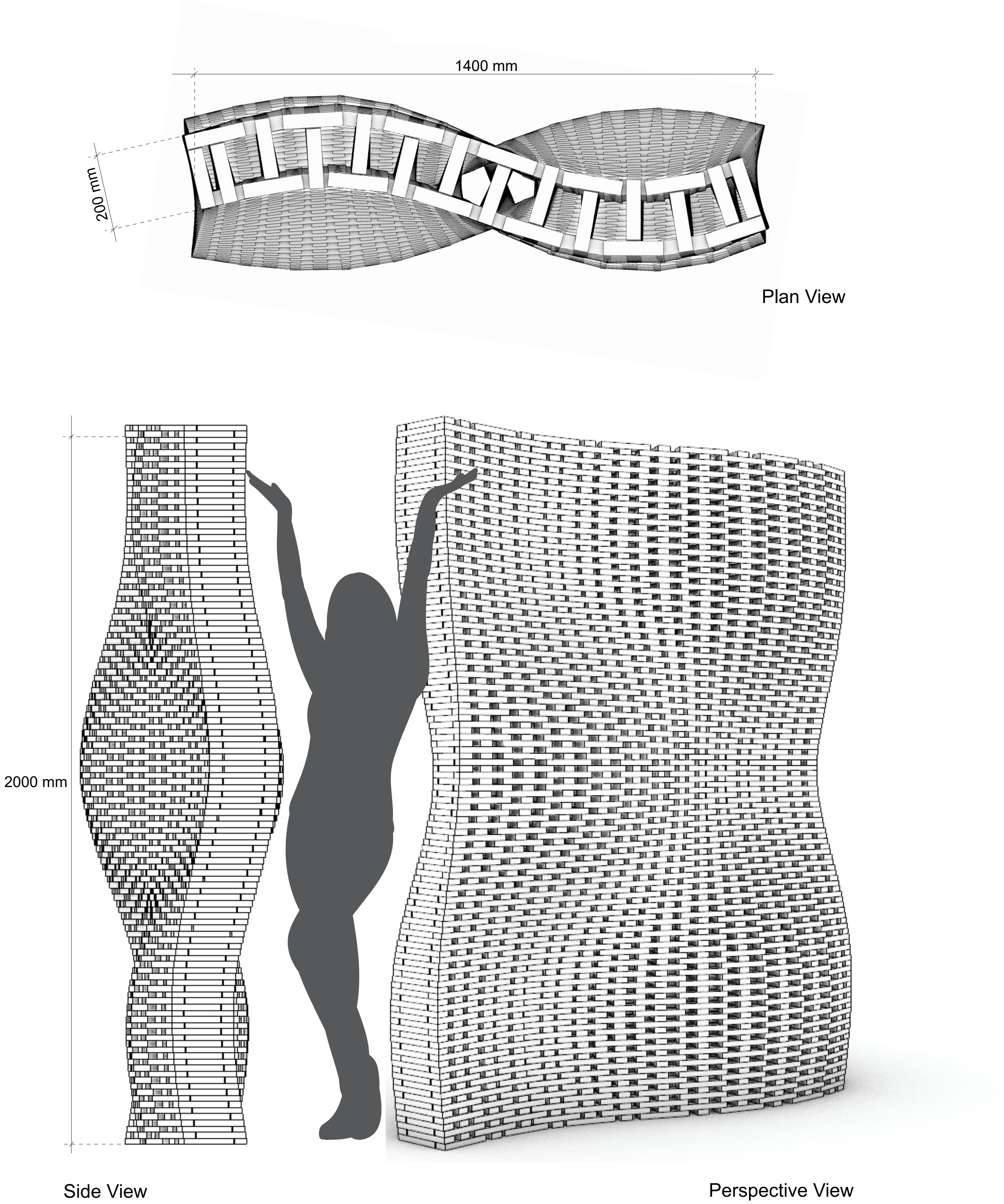

Figure 53. The proposed wall design for Experiment 1.

5.3.2 Stability Analysis

As discussed in 4.4.2, the structure can be made self supporting through three means: the timber slat elements' inherent structural capacity, their overlapping arrangement, and the connections between them. Therefore, the adhesive strength and overlapping of the components played key roles in the wall's structural stability.

The wall's stability should be checked at two stages; firstly, throughout the assembly process, and, secondly, once the structure is complete. To prevent collapse during robotic assembly, the centre of gravity (CG) for each of the five sections of the wall was controlled through the computational design tool, which checks pivot volume control every time a component is added to the structure. In case of any chance of collapse, an error warning would occur in the script (Figure 54).

For the final wall structure, the overlapping volume of components was checked through the script as follows, in order to be sure that an acceptable overlap of elements was incorporated into the design.

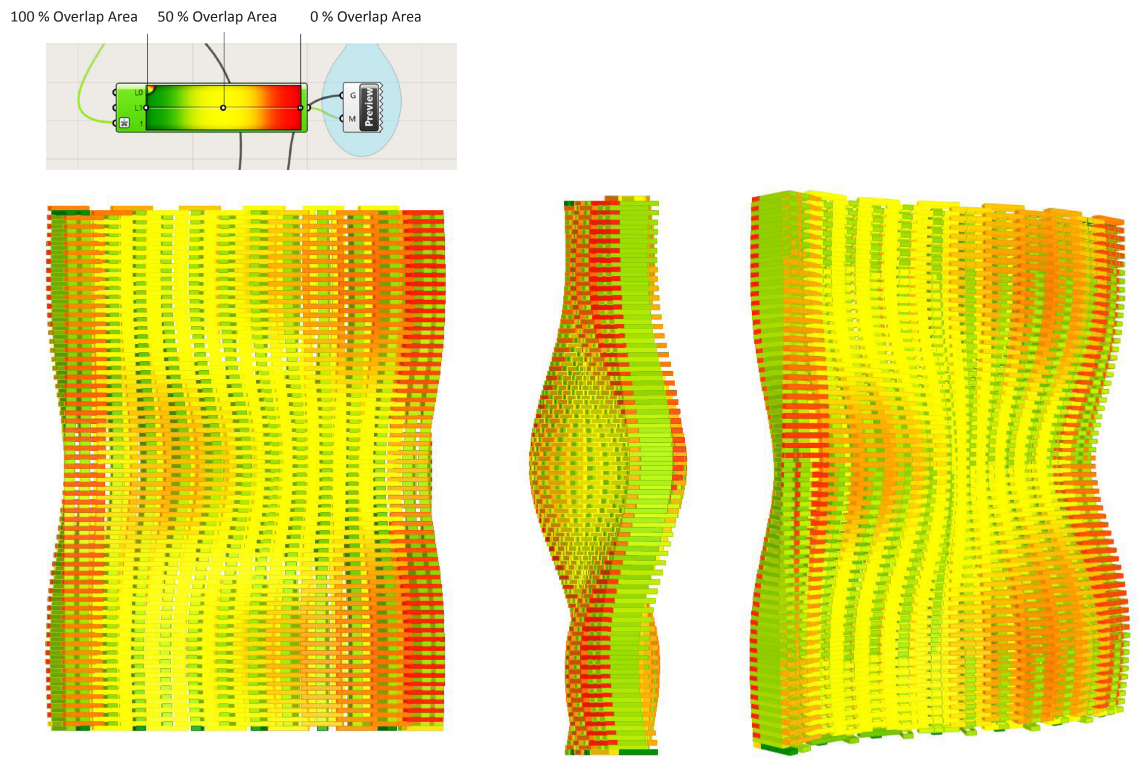

Figure 54. The stability control diagram of the wall structure.

5.3.3 Robotic Set-Up and Mechanical Tooling

The robot was mounted on a tabletop 1200 mm x 2400 mm in size. The physical boundaries of the workspace are set according to the robot's reach and its spatial layout. Since the structure is designed to be built using standard-sized components, the general fabrication process and layout that was previously described in section 5.2.1 was used (Figure 50).

5.3.4 Material System

As mentioned in section 5.2.3, the 1" x 2" x 8' lumber (17 x 37 x 2438 mm) is the main material for the system. However, for this first experiment, the pieces that are fed to the robot as the standard-sized modules are 1" x 2" x 6" (17 x 37 x 152 mm), and components were cut to size prior to fabrication, ready to be used (Figure 55).

Figure 55. The pre-cut, standard-sized components used in Experiment 1.

5.3.5 Fabrication Process

To mimic the manual assembly task of placing standard components, the grasping capability of the human hand was reassigned to the robot's gripper.[185] The picking place for the gripper was predetermined, and it is important that components are ready for gripping at that precise, predefined position because there is no sensor to provide feedback to the robot.

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[185] Ibid.

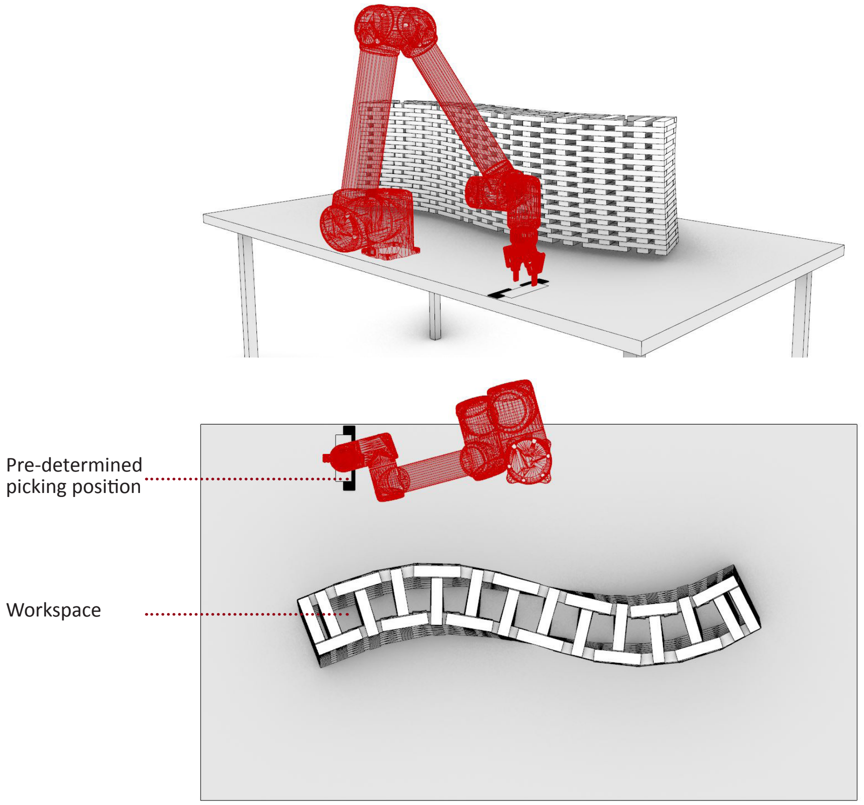


Figure 56. The robotic set-up that is used for Experiment 1: (top) perspective view; (bottom) plan view.

The feeding system is manual, and a technician physically supplies components to the picking position. Regarding the bonding process, the adhesive is applied in a semi-automated way. The adhesive is manually brushed onto the bottom face of the grasped component, which the robot is programmed to rotate and hold in a pause position for ten seconds. Afterwards, the element is ready for positioning into place (Figures 56, 57, & 59).

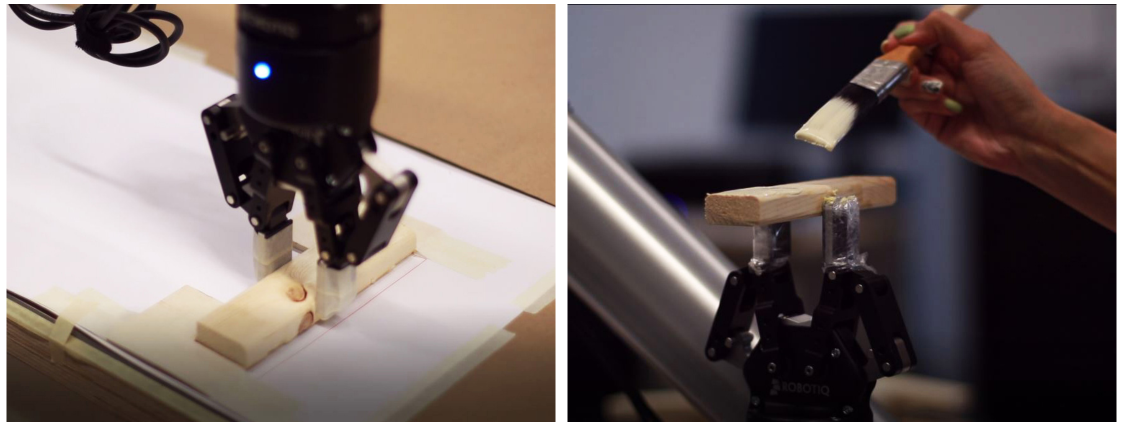


Figure 57. Captures of fabrication process of Experiment 1: (left) the predetermined picking place; (right) the semi-automated bonding process.

A motion strategy was developed to control the robot in order to prevent unforeseen movements. This control was achieved by moving the robot along a linear axis (using Move L) on the top course of the wall, by keeping the robot's position relative to component placement the same. Therefore, minimal changes in axis value occurred and the axes of the robot were nearly the same for each component in the same layer.

This strategy was developed in response to an error during one of the initial tests. Because of the relation between the picking place position and some components' placing position, the robot stopped working due to a possible collision error between its axes. In order to solve the error, one extra point was added to the robot toolpath between the adhesive applied position and the placing position. The robot was asked to go to that position every time, and start moving toward the placing position from there (Figure 58).

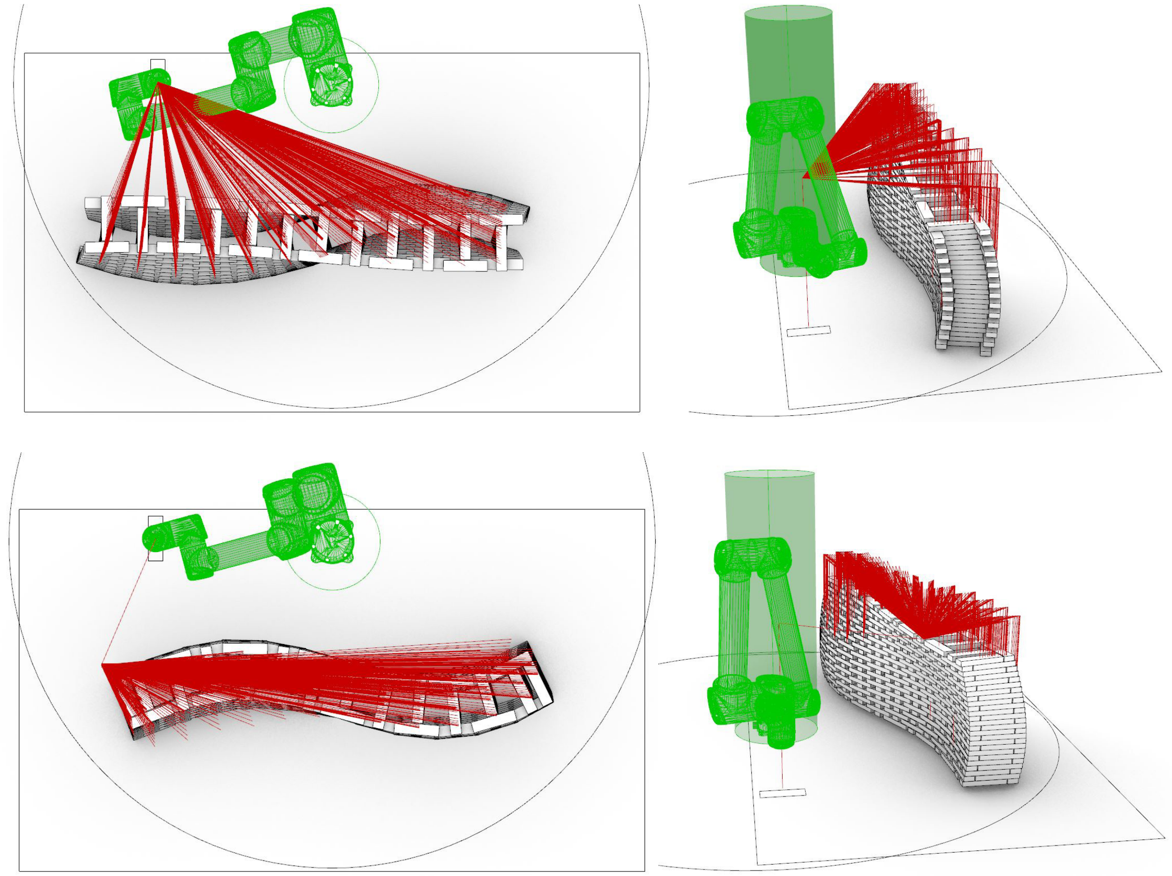


Figure 58. Motion strategy of Experiment 1: (top) collision possibility between robot's axes due to the relation of the picking place position and some components' placing position; (bottom) diagram of the proposed motion strategy.

Figure 59. Captures of fabrication process of Experiment 1.

5.3.6 Assembly Process of Fabricated Pieces

Zipbolts were chosen as connectors on both sides of the wall sections for this early prototype (Figure 60).This strategy was used here as it also facilitated the assembly and disassembly of the structure for exhibition purposes.

Figure 60. Assembly strategy of fabricated pieces: (top left) Zipbolt that is used as connector; (bottom left) Zipbolt used as connector of two fabricated pieces; (right) final assembled prototype.

5.3.7 Results and Discussion

This investigation validates the hypothesis that aggregation of a complex building component is achievable out of basic materials through additive fabrication. It reveals that, while such a complex geometry and processing of a large number of elements cannot be accomplished using conventional methods, it becomes controllable through digital design and robotic assembly.

The proposed system was tested on a wall as a fundamental, space-creating building component, producing a complex, free-form, stand-alone structure. The unique visual effect of the wall was achieved through the highly articulated arrangement and exact-to-the-millimetre alignment of components, which are only feasible through robotic assembly. The experiment demonstrates the applicability of the proposed system through robotic assembly at an architectural scale.

It should be mentioned that the dimensional tolerances and imprecision of the components can present issues for fabrication; this was discovered when low-grade commercially available and inexpensive products were used, as significant dimensional differences can be encountered within components. This issue is compounded by using a highly precise, digitally controlled robotic assembly process. The dimensional inaccuracy and shape deformation of the wood components caused accumulated error, resulting in challenges during the fabrication process as well as global deviations in the final shape of the assembled piece. This, in turn, led to gap variances in the assembly of the wall sections as the final structure (Figure 65).

The final prototype demonstrates a continuous, double-curved wall surface assembled out of a large number of discrete, standard-sized wood elements. Choosing wood as the main material for the experiment allows it to benefit from a generic, standardized, industrial product. Since wood also allows for the manipulation of its geometry during fabrication, its minimal customization during the assembly process was the main focus of the following experiment.

Figure 65. The accumulated error due to the dimensional tolerances and imprecision of components: (left) the accumulated error of fabricated piece; (right) gap variances in the assembly of two sections due to the accumulated error.

5.4 Experiment 2: Tête-à-tête: Adaptive Fabrication Method for Robotic Stacking with Non-standard Components

5.4.1 Design

For the second experiment, the design implications of a robotic assembly process of the same “T” configuration system were explored through a piece of furniture built using non-standard components. The aim was to investigate the stacked “T” system in a different orientation; the structure is designed to be stacked vertically, and to be used horizontally as bench. The bench, with a 2400 mm length, 900 mm width, and 300-550 mm height, was designed as a double-face wall system with a footprint of 900 mm length, 300-550 mm width and 2400 mm height. While the 900 mm length was suitable to be placed within the area of the robot’s possible reach, the 2400 mm height (bench’s length) is divided and assembled in seven sections. The double-face structural system means that the top and bottom faces of the bench (since the two faces of the system can adopt altered geometry in curvature, and each face played a role as the top and bottom surfaces of the bench) can be designed separately, suitable to its functionality (Figure 66).

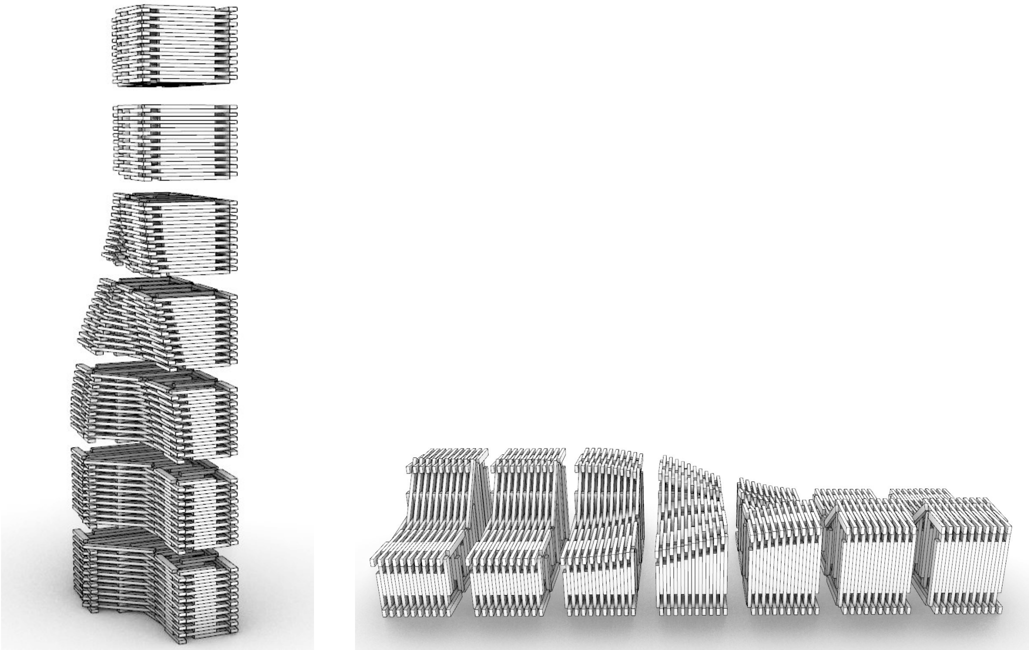
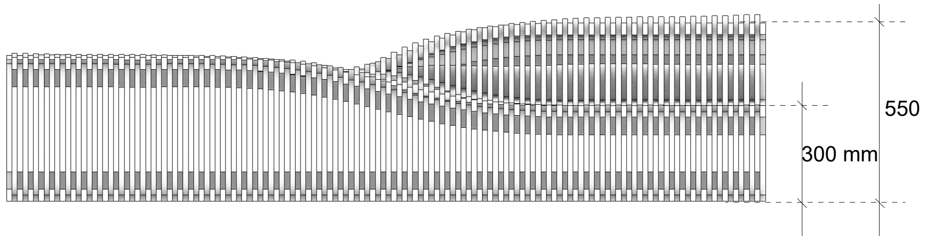
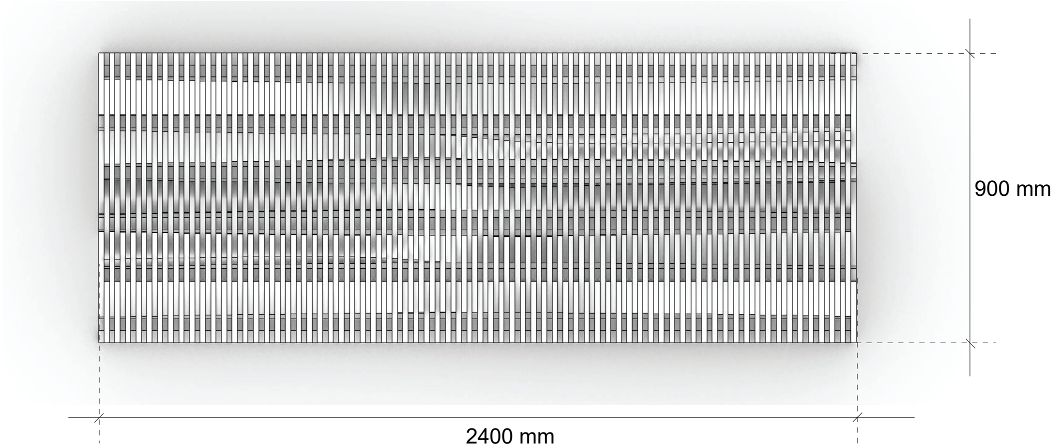


Figure 66. The proposed bench design is divided to seven sections: (left) double-face structure system is designed to be stacked vertically; (left) the horizontal form of the structure system as a bench.

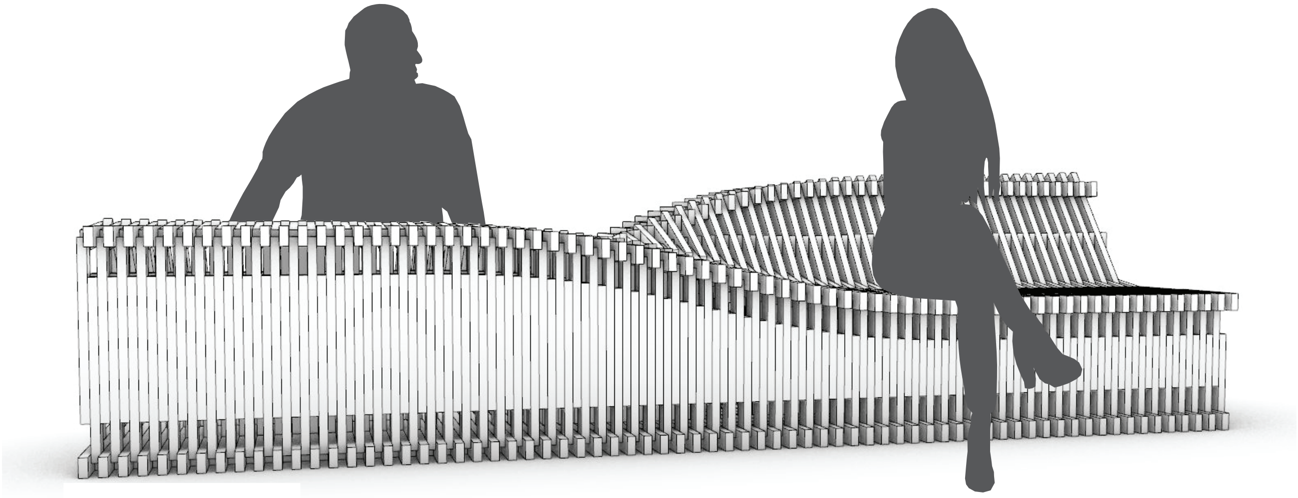
The following drawings illustrate the proposed design for the Experiment 2 prototype (Figure 67).



Front ElevationView

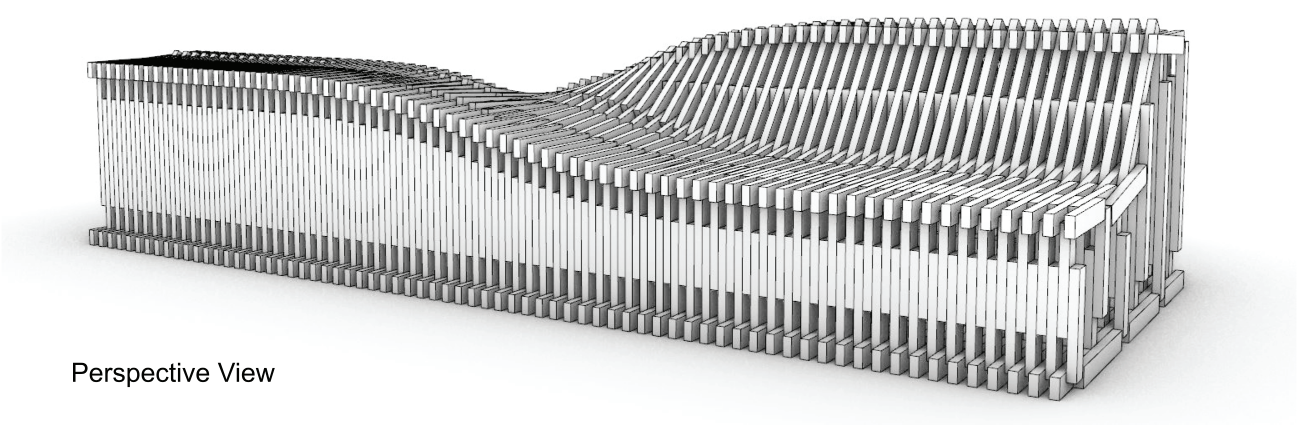


Plan View

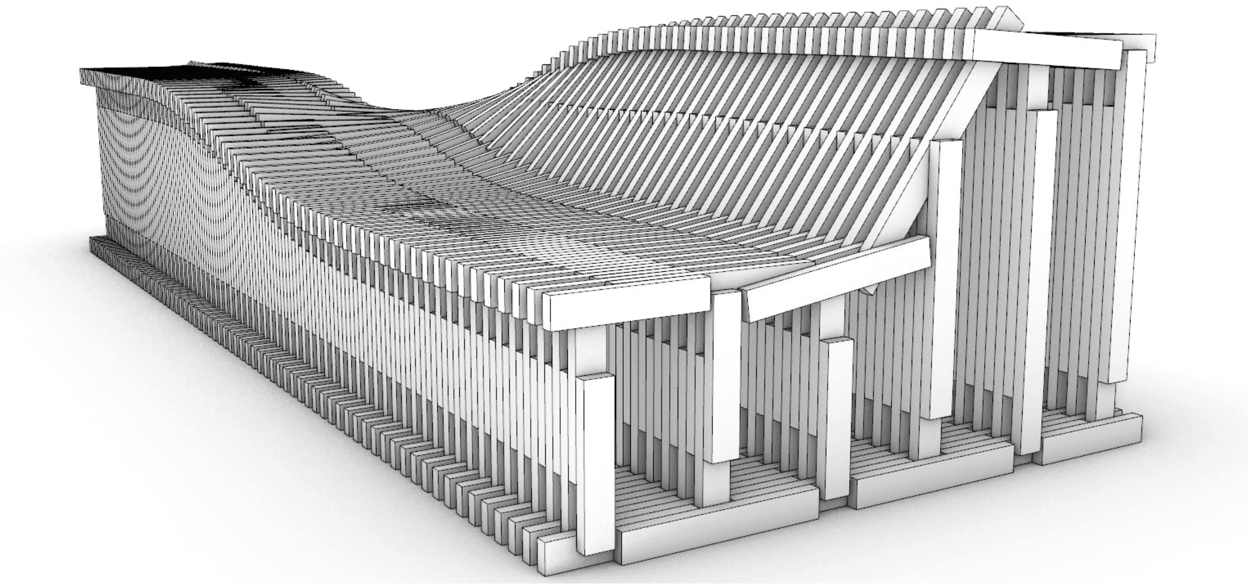


Perspective View

Figure 67. The proposed bench design for Experiment 2.



Perspective View



Perspective View

5.4.2 Stability Analysis

An exact structural calculation and analysis have been not conducted for this experiment since it was not the focus of this research; however, a potential structural analysis of the system is detailed below.

Since the system is proposed to be applied in a different orientation for this experiment, the structural modules are defined as follows: each structural module consists of two groups of “T”, upper T and lower inverted T. These two groups of T’s are connected through their tail parts. The gravity load is applied to the upper T’s head. The force transfers to the T’s tails and then the inverted T’s tails. The force has to transfer through the shear interface between the upper T’s and lower T’s tails. Finally, the force transfers to the lower T’s head and, lastly, to the ground (Figure 68).

Besides the overall structural system, it should be noted that the wood and adhesive components should be chosen based on the required strength (compressive, shear, and tensile) with respect to applied forces. The threshold of required overlap could be calculated and considered in the design script according to the applied gravity and shear forces.

Finally, similar to other projects, for example the Sequential Roof, the structural calculation should be tested by means of physical experiment.[186]

The bench structure was tested experimentally, and it’s structural stiffness worked well although a structural analytical model was not provided.

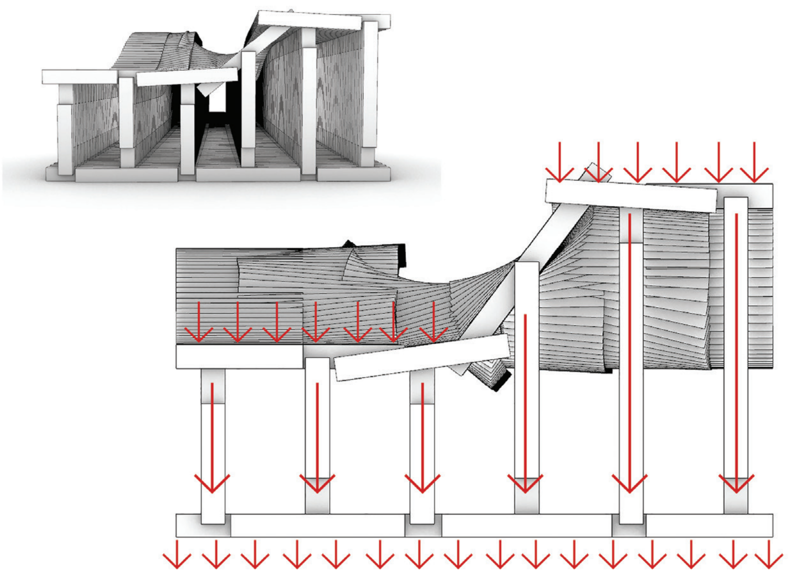


Figure 68. The structural stability analysis diagram of bench.

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[186] Menges, Schwinn, and Krieg, “Advancing Wood Architecture.”

5.4.3 Robotic Set-Up and Mechanical Tooling

The robot was mounted on a tabletop 1200 mm x 3000 mm in size. As indicated in previous sections, the physical boundaries of the workspace are set according to the robot’s reach and its spatial layout. Since the structure is designed to be built using components with various lengths, the cutting step was incorporated into the fabrication process (robotic assembly through non-standard components). The general fabrication process and layout that was previously described in section 5.2.1 was expanded (Figure 69).

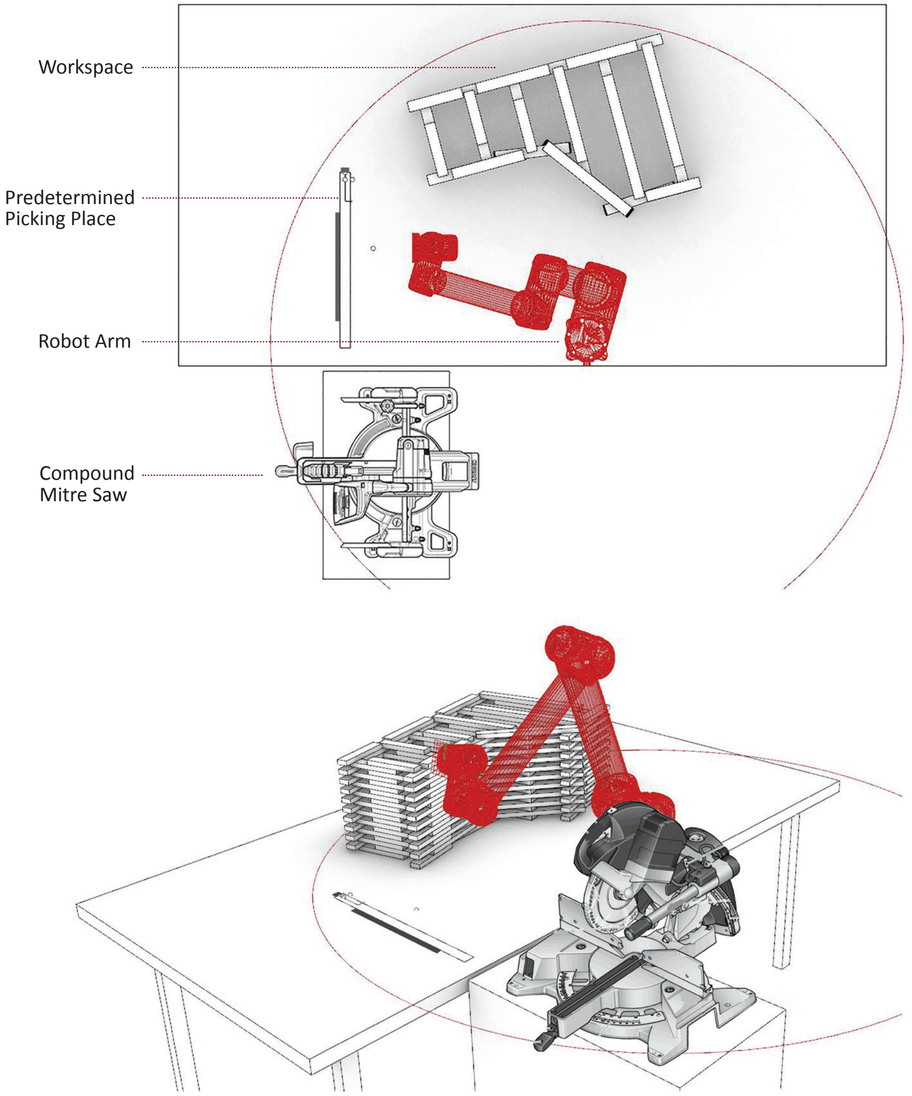

Figure 69. The robotic set-up that is used for Experiment 2: (top) plan view; (bottom) perspective view.

A compound mitre saw was added to the process as a cutting machine with the following specifications (Figure 70). In order to optimize the speed of the fabrication process and to simplify the robot's path, the picking, cutting, and gluing positions were located on one side of the table close to each other, as can be seen in Figure 71.

Figure 70. The compound mitre saw that is used in the Experiment 2.

Because there is a minimum space required between the saw's back fence and where the component would be placed on the saw bed (due to the external shape of the two-finger gripper), a second back fence is required to be built in order to support the component while it is cut. An ancillary board was designed and attached to the compound mitre saw (Figure 72).

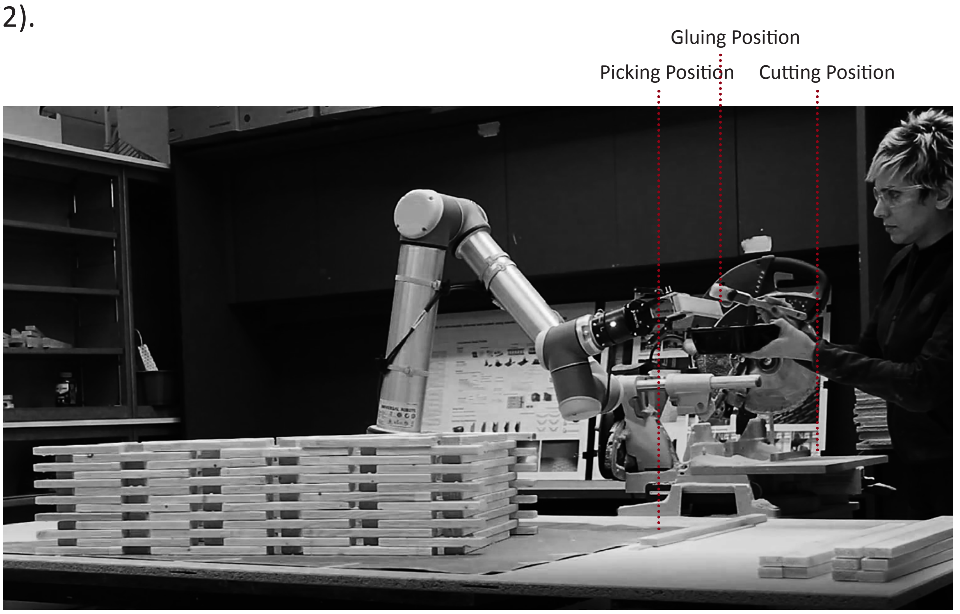

Figure 71. Image of the robotic set-up of Experiment 2. The picking, cutting and gluing positions are considered close to each other on one side of the table.

To facilitate the cutting of components during the fabrication process, components were picked from one end, leaving the other end free to be cut to the precise length required. In order to prevent tilting when the component is picked from one end, and in order to increase the area of gripping, a custom support tool was developed for the gripper (Figure 73).

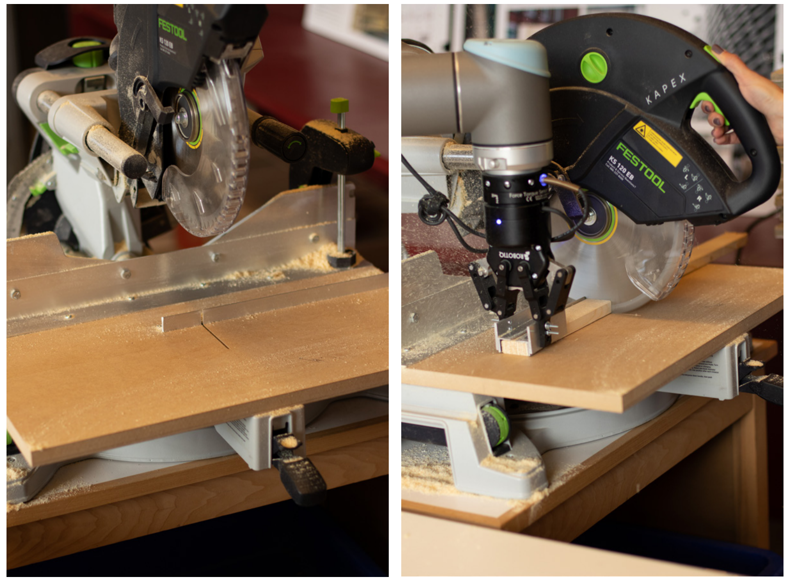

Figure 72. The board that is attached to the saw to providing another back support for where a component will be placed.

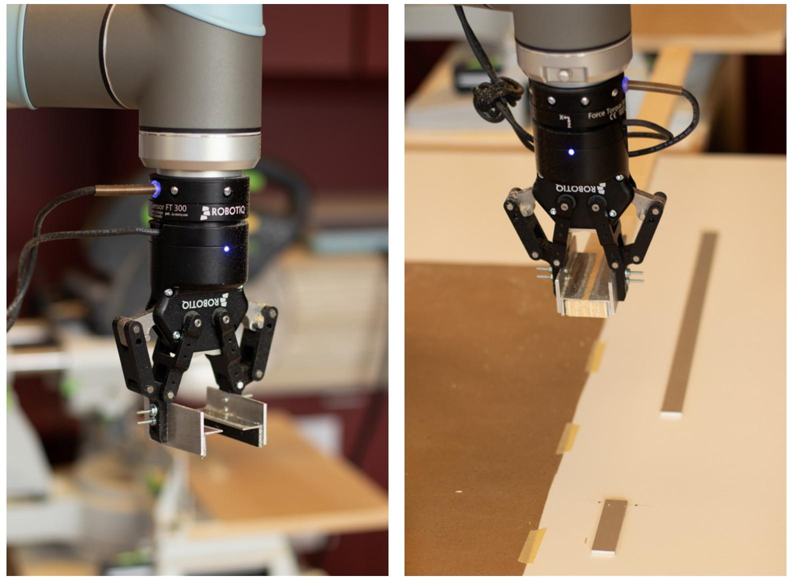

Figure 73. The custom tool that is added to the gripper to support the grasped component and prevent tilting.

5.4.4 Material System

As mentioned in section 5.2.3, the 1” x 2” x 8’ (17 x 37 x 2438 mm) lumber is the main material for the system. For this second experiment, the pieces that are fed to the robot are 1” x 2” x 24” (17 x 37 x 610 mm). Considering the physical boundaries of the workspace, which is set according to the robot’s reach and its spatial layout, pieces sized 1” x 2” x 24” (17 x 37 x 610 mm) are chosen as a feeding material to the robot. The minimum and the maximum lengths of components are considered in a domain range of numbers clarified in the following. There is a minimum distance requirement for the robot arm when it is placed close to the saw due to the spatial shapes of both the robot and the saw; therefore, the component‘s length cannot be less than that required distance. The maximum length is determined by the robot’s reach limitation. The length variation range is thus between 175 mm and 550 mm (minimum required distance between the robot and the saw to prevent collision, and the maximum possible length for the timber slat with regard to the robot’s reach limitation, respectively). Therefore, the material provided to the robot has a length of 610 mm (Figure 74).

Figure 74. The material that is provided to the robot for Experiment 2.

5.4.5 Fabrication Process

The picking place for the timber components is predetermined, as in Experiment 1. The feeding system is manual, with a technician supplying the 1” x 2” x 24” (17 x 37 x 610 mm) timber stick to the picking position ready to be grasped by the robot’s two-finger gripper. Since the structure is designed to be built using components of varying lengths, they are picked from a referenced end, ready to be positioned on the saw bed to be cut to a defined length. Same as before, in a semi-automated process, the adhesive is manually brushed onto the bottom face of the grasped component right after the element is cut, while the robot rotates and holds it in a pause position for a few seconds. Finally, the component is ready to be placed in its target position (Figures 75 & 76).

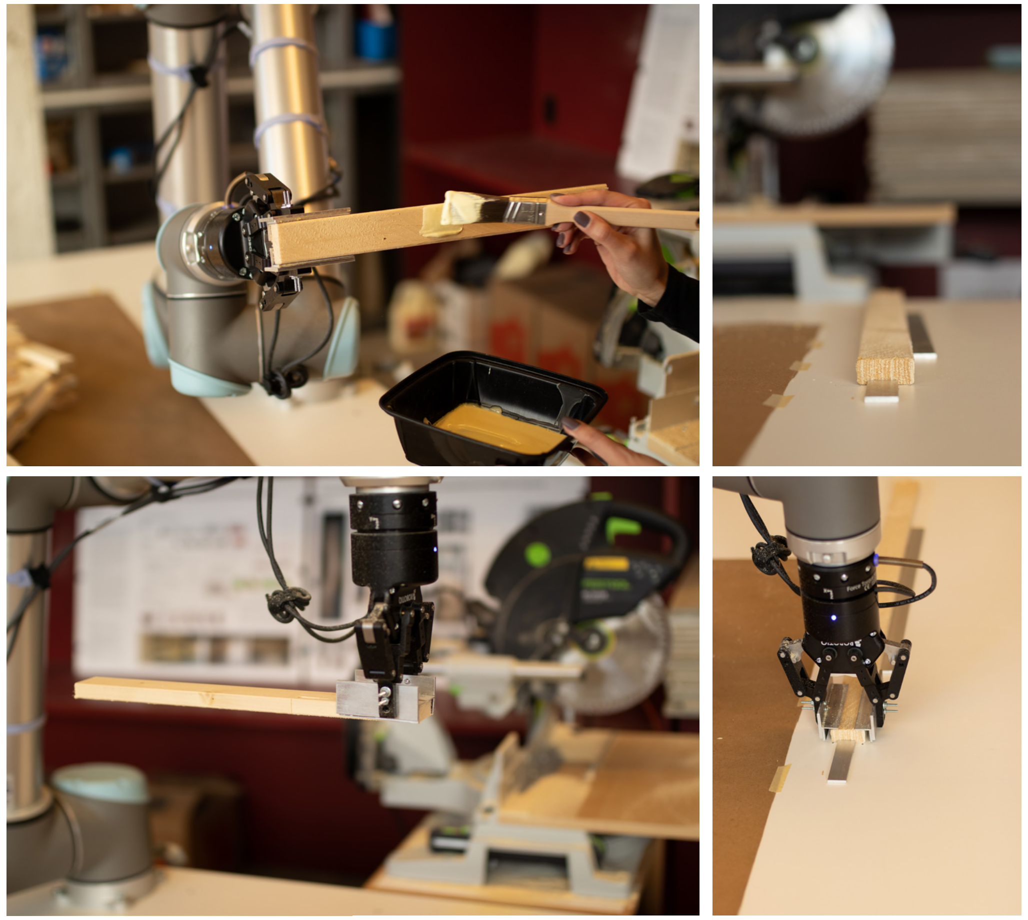

Figure 75. Captures from fabrication process of Experiment 2: (top left) the semi-automated gluing process; (top right) the predetermined picking place; (bottom left& right) the component grasped from one end.

Figure 76. Captures of the fabrication process of Experiment 2.

Since the components are customized in length through fabrication, a strategy should be considered for placing components depending on their positions in the "T" configuration system. In Experiment 1, considering the two reverse Ts, first the T's heads are placed and, later, the T's tails. Since the two-finger gripper grasped the component in the middle, there was no possibility of collision between the placing of the T's tails with the previously placed T's heads close to them. However, for Experiment 2, the components are grasped from one end. After the T's heads are placed, the direction of placing the T's tails is important to avoid collision between the placing of the T's tail with the already placed T's heads close to it (Figure 77).

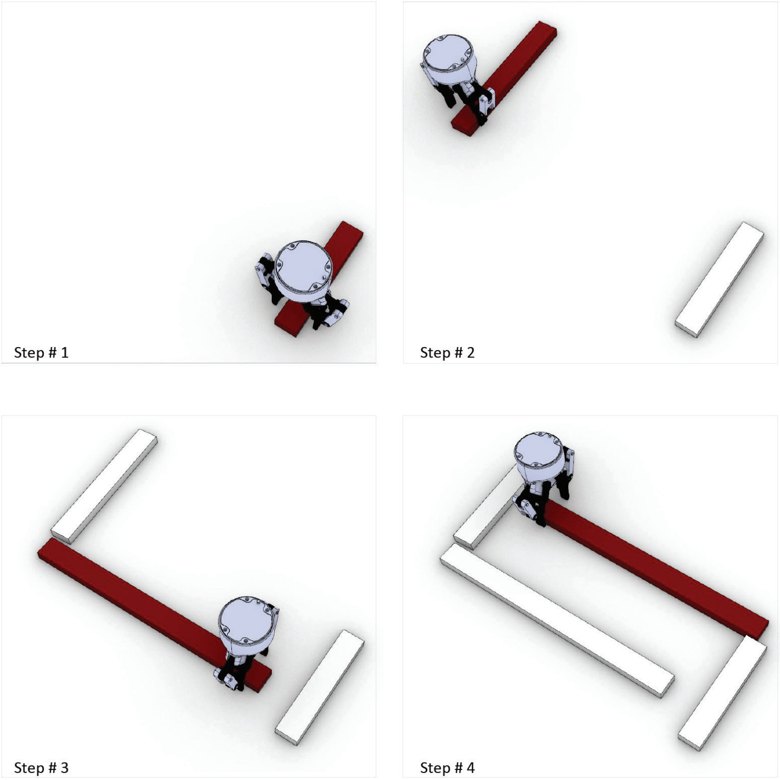

Figure 77. The placing strategy that is developed in order to prevent collision between components.

The robot's wrist needs to be rotated 180 degrees every time for placement of the T's tail. This motion strategy was considered to control the direction of the robot's wrist rotation throughout the robot's movement for two reasons: firstly, in order to prevent the possible collision between the grasped longer components with the robot axes and, secondly, considering that the robot cannot rotate 360 degrees continuously. The following figures illustrate these errors that were experienced throughout the experiment (Figure 78).

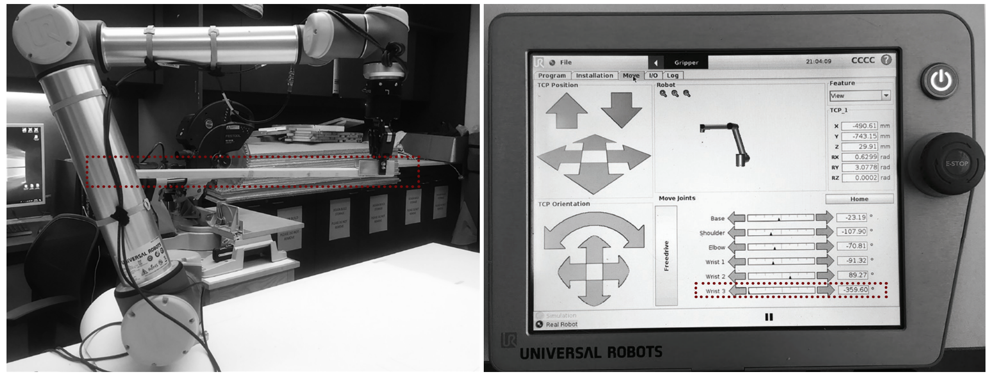

Figure 78. Two errors that force the development of specific placing strategy:
(left) the possible collision between the grasped longer component and the robot axes;
(right) the robot's limitation in continuously rotating 360 degrees that occurred as an error.

5.4.6 Assembly Process of Fabricated Pieces

As in Experiment 1, Zipbolts were chosen as the section-to-section connectors, which facilitates the assembly and disassembly of the structure. The dowel-type steel pin with the corresponding hole is used to ensure accurate positioning and provides additional support to hold the sections together. Four connectors, two on the bottom and two on either side, are located inside the sections to fasten them to each other (Figure 79). Seven sections are assembled together, forming the final bench structure.

Figure 79. The assembly strategy of the fabricated sections. Zipbolts are chosen as connectors.

5.4.7 Results and Discussion

The proposed system tested for a bench, investigating the fabrication system in a different structure. Similar to the first experiment, the degree of automation of the robotic assembly process was low and the robot was used where its digital control became vital. There were also similar challenges experienced throughout the fabrication process. However, two features make this experiment stand out from the first.

First, the possibility of varying the component length in the system developed and tested in this experiment presents greater design flexibility than Experiment 1. Within this proposed system, the structure's height and the curvature of the top and bottom faces can be adapted according to design requirements, creating non-standard structures. Such a structure built of non-standard timber components could open up entirely new possibilities for this material system. Its functional and aesthetic properties could be expanded on in architecture and construction.

While the two surfaces (the top and bottom of the bench) work functionally and structurally in a unified system, each surface has its unique geometry. The top surface of the bench is formed from a discrete layering of single elements in a constantly graded arrangement, providing the seating and support functionality of the bench in a seamless movement. This rhythmic repetition of additive stacked timber elements, with their gradually shift in orientation and length (which Gramazio discusses in *The Robotic Touch* in relation to the Sequential Roof project) blurs the boundaries between the generic and the specific, the standard and the individual.[187] Such complexity is obviously not achieva
tional techniques.

Second, the two-dimensional nature of the stacking process could be considered to be one of the main limitations of the system. However, the potential to change the global orientation of the proposed "T" system, which was explored in this experiment, offers a very promising outlook for other applications. The potential of using the system in a different orientation expands the design and functional possibilities that the structure can have in architectural applications.

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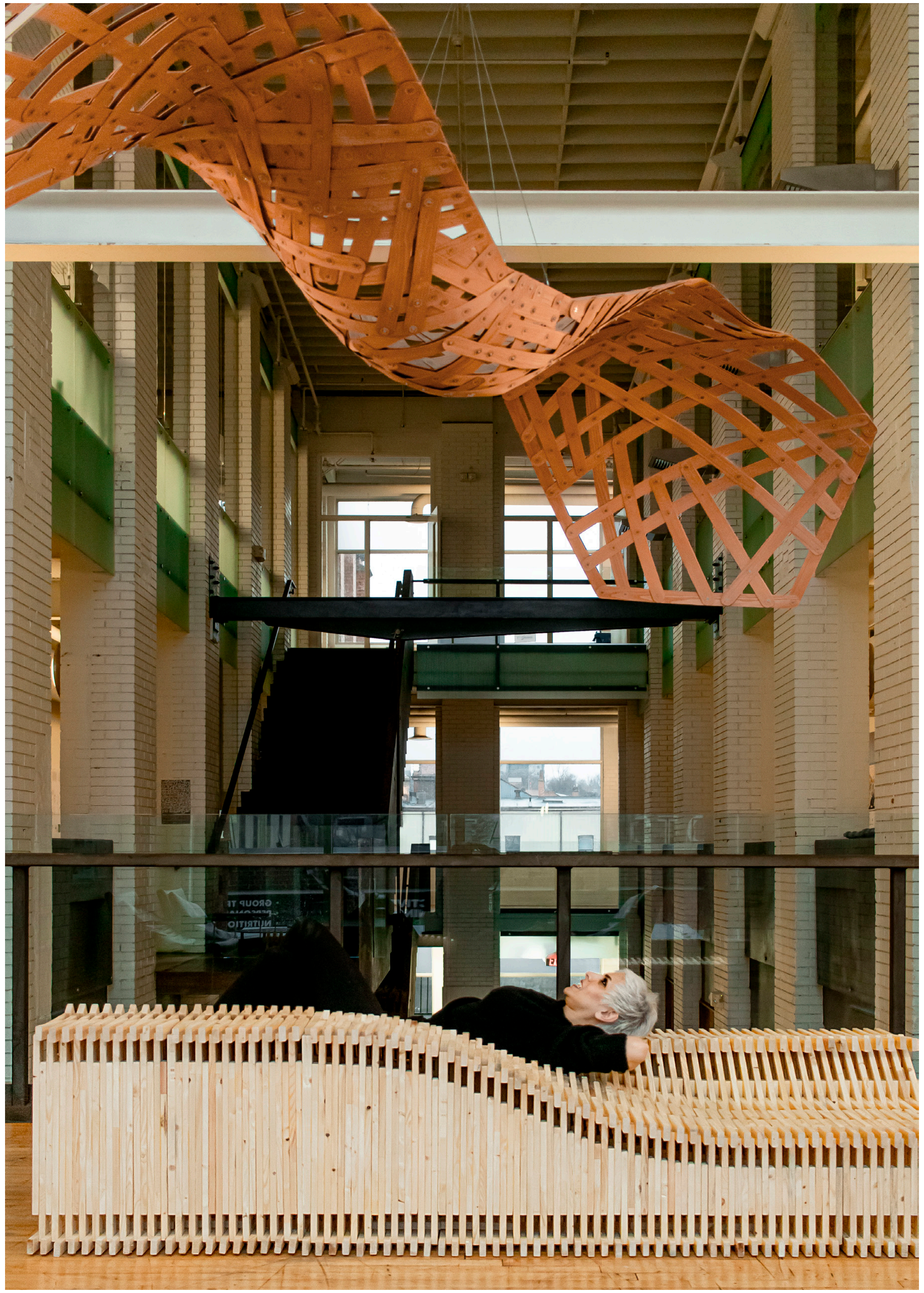
[187] Gramazio, Kohler, and Willmann, *The Robotic Touch*.



6.CONCLUSION

6. Conclusion

In this thesis, a fabrication model was developed for a robotically assembled, free-form timber structure, with its corresponding design systems and principles. The synchronization of digital design and robotic assembly was investigated through two physical experiments.

For both experiments, the robot's ability for precise positioning was employed as part of design exploration, presenting new architectural potentials for a robotically assembled timber structure. The robot's ability to control a large number of elements enables the creation of a highly articulated timber structure. The concept was to combine the benefits of automation, like repeatability and consistent quality, with the characteristics of custom production, like variation and differentiation. In other words, the industrial robot was employed not as a mass-produced product machine, but with the goal of mass producing unique pieces in order to establish a closer link between robotic design research and contemporary building practice.

The design strategies along with the assembly procedures comprise the final product. The design was informed by the parameters of the robotic assembly process and the assembly process itself was developed according to the design intent. While the aim was to optimize the structural, formal, and aesthetic potentials of a hybrid system, the combined use of both standard and non-standard units is advantageous. While there is a wide range of material that could be used for the presented system, wood was selected due to its simplicity, which permits a vast degree of freedom in assembly, and its workability, which allows for custom manipulation during the fabrication process.

The combined results of both experiments demonstrate a key contribution of this thesis, which is a new robotic-based production methodology for a stacked timber structure. Within this method, architectural design and physical assembly are directly unified in automated building-component production. Through the careful consideration of material use, structural logic, and assembly process emerges a constructive system that can be employed at an architectural scale.

6.1 Architectural Implications

The architectural system presented in this thesis can be adapted for manufacturing processes at various scales and for different uses, such as a comprehensive structural system, or adopted as a building component, interior separator, the screen of a façade, or an art installation. An irregularly shaped timber structure composed of standard modular elements results in differentiation, high resolution, and precision. While its digital logic and material system enhances its architectural properties through an intimate dialogue, structural stability, transparency, and form adaptation are also achievable within the overall structure.

While the additive fabrication of standard and non-standard components allows for the aggregation of a very complex building component, it also offers vast freedom within the structural system. The freedom enabled by the system in turn allows plane surfaces to be seamlessly merged with curved surfaces, creating a gentle structure that can be adapted to changes in the environment.

The degree of freedom within the constructive system, the “T” configuration system and material customization, blurs the boundaries between architectural elements, creating architectural space. The continuously graded arrangement of discrete layers of single timber components creates a seamless spatial differentiation through a continuous surface, resulting in a rich contemporary architectural production.

The rhythmic design allows for a dynamic relation between the viewer and the artefact. According to the viewing distance and the angle of perspective, the texture, component resolution and detail of the timber assembly is perceived differently.

With its digital, parametric logic, the modular structural system creates a net-like surface with a variable density, resulting in diverse light conditions and a distinctive modulation of incoming light. The potential of the system for controlling light transmitted through the variegated thickness and contrasting solidity of the material could be varied across the structure, resulting in light differentiation in a space defined by a continuous structure.

The proposed hybrid method of the structural system provides the possibility for the system to be applied in various orientations, allowing the structure to be used for diverse functions and as different building components. While the physical experiment of the bench illustrates the potential of the system to function as a horizontal structure on a smaller scale, it could possibly function as a truss, roof, or non-structural ceiling structure at a larger building scale. While component length customization allows the structural performance of the roof to be improved and optimized, the spatial density variation that is available through the "T" configuration system would provide for the coordination of the structure within other subsystems, such as the mechanical system.

The proposed integrated structural system, its structural stability, and the on-site assembly of pre-fabricated sections, enable the structure to be customized into infinite architectural design concepts. The Hollow, composed of 5,600 units forming hundreds of layers assembled into a vessel, is proposed as a shelter and a winter hut. This design illustrates the seamless transition between the horizontally and vertically stacked components, creating space in the form of a continuous surface while being architecturally differentiated.

In summary, the combination of digital design and computational power, along with the robot's ability to perform highly precise movements and material manipulation allows the architect to create building elements with varying functionality and aesthetic aspects.[188]

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[188] Bonwetsch, "Robotically Assembled Brickwork."

6.2 Future Challenges and Research

This thesis discusses a new use of robots in architecture by focusing on the design features and architectural potential of a robotically stacked, non-standard timber structure. However, not all aspects can be investigated deeply within the scope of this thesis work. In order to develop the application of this system in a real-world architectural context, further research is required. Below are some further investigations that could be considered as future development stages for this research.

6.2.1 Expanding the Robotic Assembly Process of Stacked Timber Structures

In terms of robotic fabrication, future development steps of the assembly process could include the feeding system, optimization of component manipulation, and the binder deposition procedure. Each of these steps could be further investigated, optimized, and possibly become fully automated. This development could include the precise application of adhesive with respect to amount and area of application.

Integrating additional sensory information into the process would also be of importance for further research and development. This integration would not only allow for the fabrication process to become fully automated; it would allow better control over assembly and enable the robot to react to unpredictable circumstances. The possibility of providing feedback to the robot also affords the ability to respond to expected challenges during fabrication; dealing with the dimensional tolerances that were experienced in both physical experiments is one example. For such a situation, if the height information of the already fabricated part could be updated throughout fabrication, it would be possible to incorporate the dimensional tolerances in real-time, therefore increasing geometric precision while minimizing instabilities.

Furthermore, it would be of interest to optimize the material system by designing it to work with both standard and non-standard components simultaneously. This idea would not only be considered as part of the design concept, but could also be incorporated as part of the fabrication procedure by equipping the robot with 3D-vision equipment. Considering material optimization is one of the important points that would increase material use efficiency and place this research one step closer to being used in the building industry.

6.2.2 Exploring the Prefabrication System of Stacked Timber Structures

Since prefabrication was considered as the option for the proposed system according to the robot's reach limitation, the issues of assembly, transportation, and installation become crucial. Some basic ideas were discussed as options at a conceptual stage for layout, geometry, and connection strategies for the design and fabrication of the wall system in Chapter Four. However, more in-depth research, detail explorations, and physical experiments would need to be conducted in further investigations. At a larger architectural scale, while the structural capability of connections would be vital to be explored and tested experimentally, the possibilities of the connection strategy to be fabricated as part of the robotic fabrication process would be significant.

6.2.3 Exploring the "T" Configuration System in a Building-Scale Solution

The development of the "T" configuration system as a building envelope could be of interest. Therefore, the potential development of the proposed system to meet the requirements of building component specifications could form the basis of further investigation. Load-bearing capacities and an insulation system would be two central factors of this research.

While the calculation of structural capability was discussed as a facet of the system to be analyzed, it was not considered for the specific requirements of either of the two physical experiments discussed in this thesis research. It would be valuable if, in further research, the proposed timber structure was calculated and designed according to real-world parameters. This would allow a better understanding of the structural capacity of the proposed design system in relation to its spatial configuration. Additionally, a deeper understanding of the structural behaviour of the material system, wood and adhesive, is necessary in order to move the research closer to use in the building industry.

The possibility of applying insulation in the hollow core of the "T" configuration system could also be investigated as a further development to transfer the system into a building-scale solution.

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