The Brick Labyrinth

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Abstract. This paper presents a project developed within the Master of Advanced Studies in Architecture and Digital Fabrication programme at ETH Zurich. The Brick Labyrinth is the first large-scale construction built in the Robotic Fabrication Laboratory, a unique multi-robotic setup for automated prefabrication at architectural scale. The project continues the tradition of robotic brick laying started at Gramazio Kohler Research but increases the significance of computational design and robotic control by solely working with a dry-stacked construction method. The paper introduces the design methodology, the computational framework and the robotic fabrication setup and addresses the structural challenges of the constructive system. It introduces strategies for an automated multi-robotic brick laying process at large-scale including custom-made robotic end-effectors to increase the speed of the process. The unique setup of the project and its material system demonstrate a fully reversible construction process at architectural scale, suggesting a new approach to physical prototyping, which could fundamentally change the way we design buildings. While this paper highlights the design explorations leading towards the final structure - featuring the development of a flexible dry-stacked brick bond and its potential to create unique spatial sequences - it also provides an outlook on how the integration of computational tools into automated fabrication processes can lead to new design typologies.

Keywords: Digital Fabrication · Computational design · Robotic fabrication · Robotic brick laying · Stability analysis · Dry-stacked masonry · Labyrinth

1 Introduction

The project presented here was devised and conducted over the course of three months as part of the Master in Advanced Studies in Architecture and Digital Fabrication curriculum at ETH Zurich, a programme that teaches fundamental methods and technologies of digital design and their 1:1 scale implementation in architecture and construction [1]. Through iterations of design studies and physical prototyping, the team of 17 students together with the support of tutors and researchers developed the project starting from the design brief and constructive system to the final design and its construction. Simultaneously, they optimised the robotic setup and mechanic end-effectors, as well as the structural simulation and fabrication procedure, to enable an efficient robotic construction process (Fig. 1).

Fig. 1. The Brick Labyrinth in the Robotic Fabrication Laboratory at ETH Zurich, 2017

With its dimensions of 8 m by 10 m in plan and a height of 2.8 m, the Brick Labyrinth is the first large-scale construction built in the recently opened Robotic Fabrication Laboratory (RFL) [2] at ETH Zurich with its four collaborating robotic arms suspended from two gantries and a work area of 45 m by 17 m. The project continues a long tradition of robotic brick laying started by Gramazio Kohler Research in 2006 [3, 4]. However, past projects such as the Programmable Wall or Structural Oscillations relied on adhesives to achieve structural stability. For the Brick Labyrinth, conceived as a temporary structure in the RFL, reversibility demanded for a dry-stacked construction method. With the focus on structures in equilibrium, the computational design process had to integrate structural simulation and pushed the potential of robotic control as placement of each single brick required a high level of precision.

The efficiency of the inherently slow robotic pick-and-place procedure was increased by the development of a new robotic end-effector, a brick magazine that can hold a stack of eight bricks at a time and dispense them one after the other. The simultaneous use of two synchronized robotic arms suspended from one of the two gantries in the RFL further increased the speed of the process\(^1\). The final structure

\(^1\) Placing time per brick was reduced to an average of 15 s (4 min for 16 bricks). Two ABB robots each placing 8 bricks per cycle, with minimised gantry travel time. This speed was comparable to the process done in the group in 2006 setup (see [3]).
consisted of 10,135 bricks placed over the course of 19 days. Through a custom computational design and robotic control setup students developed all project stages and built multiple full-scale prototypes.

2 Design Research

2.1 Design Brief and Explorations

The assignment presented to the students asked for the design and construction of a labyrinth using the RFL robotic fabrication setup to dry stack bricks into a large-scale structure. The maximum amount of bricks was derived from the estimated construction speed of approximately 500 bricks per working day, totalling at a maximum of 12'000 bricks for the planned fabrication time of four weeks. The construction area in the RFL and the maximal construction height were given as further constraints.

In a first phase, different conceptual approaches to the architectural typology of the labyrinth were explored. The conception of a contemporary labyrinth was inspired by topics such as the relation to the human body that can be found in some of Richard Serra's work [5], the labyrinth typologies based on the loss of orientation in never-ending self-similar spaces that can be traced back to the legend of the Labyrinth of the Minotaur and the Knossos palace complex [6], and the literary work of Jorge Luis Borges, which describes both physical as well as mental vastness of labyrinths [7].

This led to a series of different design proposals that were iteratively refined. Each included the design of a labyrinth typology as well as a constructive system, a specific brick-bond with its generative and structural logic. Simultaneously the structural performance limits of the different brick-bonds were tested in real-scale physical prototypes, while the overall labyrinth designs were 3D printed and their spatial qualities evaluated as scaled models.

The developed design strategies included both surface and volumetric design approaches. The former ones were articulated through surface arrangements, single- or multi-layered, which define differentiated spatial relationships. Strategies of realising these surfaces in dry-stacked brick structures included the stiffening of walls by introducing curvature in the horizontal plane, modulation of their thickness and cavities over the vertical development to distribute and control their mass, and adding buttress elements to improve horizontal stiffness. Volumetric design approach included design concepts treating the brick as a space-filling element, articulating space through a sculptural mass. Strategies featured false-arching techniques to create vaulted or enclosed spaces, experiments with the orientation of the bricks so their perforated inner side is exposed to the view, or a field of bricks arranged in such way that it was only certain stable paths that allowed the visitors to walk on.

2.2 Final Design

The final design chosen for the Brick Labyrinth – a synthesis of several investigations – was composed of two walls spiralling into each other. The spiralling concept generated a long winding path where the differentiated walls define a series of highly articulated spaces that have a strong impact on the physical experience of the visitor. The labyrinth has two entries at a slight offset after which the visitor is guided through a sequence of changing sections towards the central open area.

Driven by this overall idea, the constructive system of dry-stacking bricks became a main design driver and one of the biggest challenges of the project. Without any additional adhesive between the elements, the structural integrity of the walls is solely depending on gravity and friction, which makes the result all the more spectacular and surprising. To push the structural capacities and the spatial flexibility of the system to its limits, a special brick bond was developed that allows the transition between four different states of the system (see Fig. 2). A simple single-layer running bond (a) transforms into a loose running bond (b) with additional bricks placed in a 90° angle increasing the structural capacity to lean out locally (c), and finally to a doubled-up leaning wall counterbalanced by connecting ribs between the two layers (d).

![Fig. 2. Different states of the developed brick bond](image)

Both walls start as a single layer running-bond, forming a nearly straight vertical extrusion at their ends. The lower part of the single-layered wall is undulating in order to increase the support polygon of the structure and allow for a curved development over the vertical axis. The doubling-up of both walls leaning towards each other creates a key moment in the spatial experience of the labyrinth (Fig. 3).
the walls. The parametrisation of these curves allowed to precisely define the domain where the brick-bond would transition from one state to the other, while the bricks would be generated and distributed through an underlying algorithmic logic. For instance, the script could solve the smooth transition from the single-layered to the double-layered wall sections and generate the appropriate amount of buttresses that would stabilize them.

3.2 Structural Stability Analysis

On a computational level, the brick bond is building up on two of the main classes of COMPAS (see [8]). The brick modules as a sub-class of the COMPAS “mesh” data structure [11] and the brick assembly as a sub-class of the COMPAS “network” data structure [12]. The network is a connectivity graph meant for the representation of networks of vertices connected by edges. In our case, every brick mesh is represented by a vertex in a network connected to its vertical and horizontal neighbouring bricks through edges, allowing for a simple equilibrium analysis based on purely geometric parameters, in this case the mass centre point of each brick and their overlap areas. A brick assembly’s stability is evaluated by iterating through its layers, starting with the top one, calculating the resultant force and its position on its supporting neighbours until the base of the wall. Multiple scenarios were analysed and abstracted in order to cover all options of the used bonds (see Fig. 4). This included a brick supported by one, two, three or four bricks. By checking if the resultant force lies in the supporting area of an underlying brick layer, it was clear at which element an unstable assembly would fail and could thus be easily adjusted. Abstraction strategies for the force transfer for situations with one, two, three or four support elements were developed. During the design process, the structural stability analysis was continuously verified with the behaviour of physical prototypes built in 1:1 scale. These prototypes helped to understand the influence of friction in geometrically unstable configurations.

3.3 Robotic Fabrication Simulation and Online Robot Control

The fabrication sequence, robot and gantry movements, material pick-up and other production related processes were modelled and simulated in ABB RobotStudio [13], using a simplified version of the RFL setup (see [2]). The communication setup

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3 COMPAS framework offers a pure Python base with flexible data structures and algorithms, independent geometry processing, interoperability with external libraries used in structural design, methods and solvers for numerical computation, high performance computing capabilities, visualization tools as well as interfaces to common CAD software and ecosystems. Full list of features and extensive documentation can be found on its GitHub webpage (see [8]).
streamed the accurate robot and gantry simulation data from the company developed proprietary software to Grasshopper and visualized it in Rhinoceros. It simulated the handling of the bricks from the feeding station to their final placement, checked for possible collisions and minimized the gantry movement to reduce production time. A separate script controlled the two UR5 [14] feeding stations as their operation could be decoupled from the main production flow. The feeding stations would prepare the brick stacks and wait for the ABB robots to pick them up before resuming operation.

The computational environment described above was also used for the online control of the robot arms and the gantry system, whereas commands could be sent directly from the computer to the RFL system (see [2]). A server connection managed the bidirectional communication from digital to physical setup, translating robotic poses defined in the computational setup to Rapid code and directly sending them to the ABB controller. Synchronization of the two robots and the flow control of the process was achieved through feedback of the execution status of each robot task (Fig. 5).

![Diagram of the computational workflow](image)

**Fig. 5.** Diagram of the computational workflow

## 4 Robotic Fabrication

### 4.1 Robotic Setup

Production took place in the RFL (see [2]) of the Institute of Technology in Architecture at ETH Zurich. It consists of two bridges with two telescopic 2-axes from which a total of four ABB IRB 4600 2.55 robotic arms are mounted upside-down, enabling every robot base to have three additional semi-independent degrees of freedom. For the purpose of this project, we used only one bridge with two ABB robots in a work area approximating 100 square meters. To speed up the process, a custom developed brick magazine⁴, able to pick up a stack of 8 bricks and deposit them one at a time, was mounted on each ABB robot. Two feeding stations placed on the periphery of the construction area completed the setup, where small-scale UR5 robot arms each assembled two stacks of eight bricks picking them from a feeding rail while the ABB robots were placing bricks in the structure. The decision of employing two different types of robots in the same process was taken in accordance with the robots’ capabilities. UR5 robots are comparatively small and have a payload of 5 kg which only serves for manipulating a single brick. As a result, they lend themselves perfectly for pre-fabricating the brick stacks. In contrast, the RFL ABB robots reach the entire workspace and can carry up to eight bricks. Human operator is controlling the collaboration between the robots, ensuring that stacks are built during the time that the ABB robots are placing the eight bricks (Fig. 6).

![Diagram of the robotic fabrication setup](image)

**Fig. 6.** Layout of the robotic construction setup in RFL with two UR5 picking stations and two ABB robots mounted on a gantry

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⁴ The 40 kg maximum payload of the robotic arm with approximately 15 kg weight of the tool itself limited the amount of bricks in the magazine to eight (8 × 3.2 kg + 15 kg = 40.6 kg).
4.2 Sequencing

The fabrication sequence of the walls was optimised for minimised gantry travel time along the X-direction, as this was the gantry’s slowest movement direction by dividing each layer of bricks into segments of 16 bricks along similar X-positions. These 16 bricks were sorted according to their Y-positions and each robot arm would place eight bricks in its sector while synchronized with the other robot in order to avoid any collisions of the robotic arms and their gantry carts. Because no mortar or construction glue is used, the brick dry-stacking process is easily reversible. The robotic disassembly process was tested on the finished structure but not used in the end due to time constraints (Fig. 7).

Fig. 7. a. Model of the brick magazine and b. ABB robots mounted on the overhead gantry picking up the preassembled brick stacks from the UR5 robot station

5 Conclusion and Outlook

Significant advances were made in the field of robotic brick laying at Gramazio Kohler Research since the first experiment in 2006 (see [3]). The technique was used for the construction of a non-standardised brick façade, as well as for multiple teaching and installation projects exploring its design space and developing new robotic brick bonds. This development is extensively documented in PhD dissertation of Tobias Bonwetsch [15]. ROB Technologies [16], a Gramazio Kohler Research spin-off, continued this research in close collaboration with Keller AG Ziegeleien [17]. In recent years there has been a strong development of in-situ robotic fabrication technologies, also applied to masonry structures [18–24].

This paper and the project described extends the existing research to robotic dry-stacking of bricks, thereby placing much emphasis on the structural challenges by including structural stability analysis into the design development. This strategy could be expanded in the future by extending the structural analysis to include friction between elements in the setup. In the project presented, friction was evaluated through physical tests at full-scale. Concerning the actual speed of construction (averaging 15 s per brick), it is evident that it is within the range of the projects done at Gramazio Kohler Research in 2006 (see [3]). However, the presented setup in RFL has a much larger building area⁵. Accordingly, one performance goal of the project was to retain a similar construction speed despite increased travel times to the feeding stations. Two strategies were applied to achieve this goal: The coordinated and synchronized control of a multi-robotic system and the use of a brick magazine that can deposit a stack of bricks. Overall, this represents a considerable improvement in efficiency compared to the 2006 setup, especially since the new setup requires only two human operators for the entire operation (one for the feeding station and another one for the construction process).

These concepts could be further improved by increasing the number of collaborating robots or the number of bricks in a magazine. Ideally, the brick magazine would be replaced by a continuous feeding system which would make the time consuming pick-and-place procedure obsolete. The project suggests a new type of rapid prototyping facility to test fully reversible structures in a completely automated setup, where design variations could be test-assembled, experienced at full architectural scale, and the material returned to its initial state “over-night”, ready to be reused. This concept could inspire a new, more ecologically sound approach of prototyping in the age of 3D printing in different scales and material systems.

In addition to the technical and computational achievements, the brick labyrinth developed and built by the students of the MAS in Architecture and Digital Fabrication created a unique spatial experience for all visitors. It shows how the integration of computational tools in automated fabrication processes can lead to new typologies that extend our architectural vocabulary.

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References


⁵ The work area of RFL is 765 m² as compared to the 2006 setup (see [3]) of around 30 m².
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