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ORIGINAL PAPER

Robotic vault: a cooperative robotic assembly method for brick vault construction

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Abstract

Geometrically complex masonry structures built with traditional techniques typically require either temporary scaffolding or skilled masons. This paper presents a novel fabrication process for the assembly of full-scale masonry vaults without the use of falsework. The fabrication method is based on a cooperative assembly approach in which two robots alternate between placement and support to first build a stable central arch. Subsequently, the construction is continued individually by the robots - building out from the central arch based on an interlocking diagonal brick sequence. This proposed method is validated through its successful implementation in a full-scale vault structure consisting of 256 glass and concrete standardized bricks. The paper includes strategies for developing the design, sequencing, and robotic assembly methods used to build the vault.

Keywords Masonry vault · Robotic brick construction · Cooperative robotic assembly · Sequence planning · Falsework-free construction

1 Introduction

Robotic assembly allows for the fabrication of irregular structures due to the ability of industrial robots to precisely position elements in space. One of the earliest applications of this was in automating bricklaying (Thomson 1904; British Pathé 1967): a repetitive process for which robotic assembly methods are well-suited. While early architectural applications (Bonwetsch et al. 2006, 2007; Dörfler et al. 2016) took advantage of a robot's capabilities to generate and assemble controlled irregular brick walls, these attempts were limited to formal explorations aimed at identifying the aesthetic potential of robotic fabrication techniques. As shown in this paper, by combining robotic precision with structural form-finding, this process can be further developed beyond creating three-dimensional decorative objects. We believe that one of the greatest potentials of robotic construction lies in taking advantage of the geometric freedom gained from this process to materialise form-found structural shapes. This can lead to a material efficient design and construction process that fully exploits the emergent potential of robotics applied to architecture.

In this paper we present the developments of a cooperative fabrication process for the construction of a full-scale masonry vault (see Fig. 1). This includes the following: (1) a description of how the fabrication method was developed, (2) the fabrication and structure-informed method underlying the design of the vault, and (3) sequencing and path-planning strategies that enable the robotic construction of spanning structures made of heavy materials (glass and concrete bricks in this project). Finally, the paper describes the implementation of this process in the construction of a $3.3 \times 2.6 \times 2.0$ m section of a masonry vault using two industrial robotic arms.

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Fig. 1 Finalised prototype of robotically assembled brick vault

2 State of the art

Robotic construction of masonry structures is one of the oldest applications of robotics in architecture. This paper extends the application of robotic bricklaying to spanning structures, which have been specially designed to eliminate the need for falsework during construction. For this reason, our review of the existing literature consists of evaluating self-supporting masonry techniques and the implementation of cooperating robots for the stable construction of complex geometries.

2.1 Robotic brick construction

Historical documents show that automating masonry work was pursued ever since the beginning of the 20th century (Thomson 1904) with the first video documentation of a functional brick-laying machine dating back to 1967 (British Pathé 1967). The goal was to automate the construction process to decrease labour time and overall costs. However, the potential of industrial robots, with regards to their precision, was first explored in 2005 with the development of differentiated brick walls (Bonwetsch et al. 2006, 2007; Kohler et al. 2014). These applications showcase how the controlled arrangement of bricks can lead to intricate geometric assemblies. These methods were further extended through the implementation of a mobile robotic brick construction process in 2014 (Dörfler et al. 2016), which enabled the robots to be employed directly on site. These projects have proved that robots in the field of architecture have significant potential for formal differentiation and construction applications—despite this, they are rarely utilised outside the domain of vertical structures, such as walls and columns (Bärtschi et al. 2010; Kohler et al. 2014), which strongly limits their application range.

2.2 Cooperative robotic assembly

Multiple robots have been used in assembly processes to increase the speed or size of the built object (Piskorec et al. 2018). Furthermore, recent developments have explored the potential of using robots cooperatively to support each other during construction (Parascho 2019). Employing two robots not only duplicates the output of a process, but also leads to new coupled behaviours that would not be possible with a single robot. For assembly purposes, cooperating robots allow for one robot to act as temporary support while the other one is placing an element. This strategy has so far only been applied to lightweight construction, such as steel space-frame structures

(Parascho et al. 2017), timber structures (Thoma et al. 2018) or Styrofoam structures (Wu and Kilian 2018). The latter of these utilizes two robotic arms for the construction of an arch; however, while the robots do act as supports, the forces inherent in constructing the arch are close to negligible, given the low density of the Styrofoam construction material. Constructing full-scale masonry shells would significantly increase the self-weight forces that must be resisted by the supporting robot, making full use of its payload capacity to hold a structure in space.

3 Research question

This paper advances the state of the art by showing that cooperative robotic fabrication is a viable method of constructing spanning masonry shell structures made of heavy materials (i.e., glass and concrete bricks). We aim to expand the current design space beyond existing robotic applications, which are often based around constructing simplified geometries that are intuitively feasible.

The goal of this research is to prove that we can leverage the potential advantages of robotic construction while also fulfilling the hard constraints of structural efficiency (i.e., building funicular vault geometries). This paper serves as proof of concept study for a novel robotic assembly method that uses a robot's capacity for precision to construct a geometrically complex doubly-curved brick vault. This fabrication process is designed in such a way that the construction of the full vault is completed without any temporary scaffolding (see Sects. 5.4 and 5.5 for more information on how the robots were used to achieve this). This is a significant improvement to traditional manual methods of masonry construction—a geometrically complex vault like this would have to be built using falsework as a temporary support structure while also using guides/templates to help place the bricks accurately in 3D space.

3.1 Description of the assembly method

The assembly method is composed of two distinct construction phases (see Fig. 2). In the first phase, the two robots cooperatively assemble a central arch. This process is based on an alternating placement strategy, where one robot acts as a placing agent while the other serves as support for the partial arch until it is completed and self-supporting (Sect. 5.4). In the second phase, bricks are added to the arch on both sides, allowing one robot to stabilise the arch from the opposite side to where a new brick is being placed. This is repeated until the entire vault is built. By following a stepwise tessellation pattern, we ensure that each brick is at all times supported on at least two sides.

4 Design of the vault structure

The design of the vault had to take into account both structural and fabrication-related parameters. The Airy's stress function form finding approach enabled the identification of a compression-only shell, which is ideal for a masonry vault where tensile stresses should be avoided. Interlocking the bricks, based on the herringbone tessellation pattern, also promoted structural stability both during fabrication and in the vault's final condition.

The fabrication setup consists of two industrial robotic arms (ABB 4600 2.55) placed on linear axis tracks (see Fig. 3). However, in this study we choose not to use the external tracks to simulate a more general on-site robotic setup. The robots in our testing facility have a reach of 2.55 m and are positioned facing each other at a distance of 3.5 m; to improve reachability and increase the span of the structure, this distance was later adjusted to 4 m. The robots' position and the added tool geometries led to two spheres of reach around each robot arm, with a radius of 2.55 m and an intersection volume 2 m in height.

The robotic fabrication method and setup influence the design process through the following two criteria: (1)

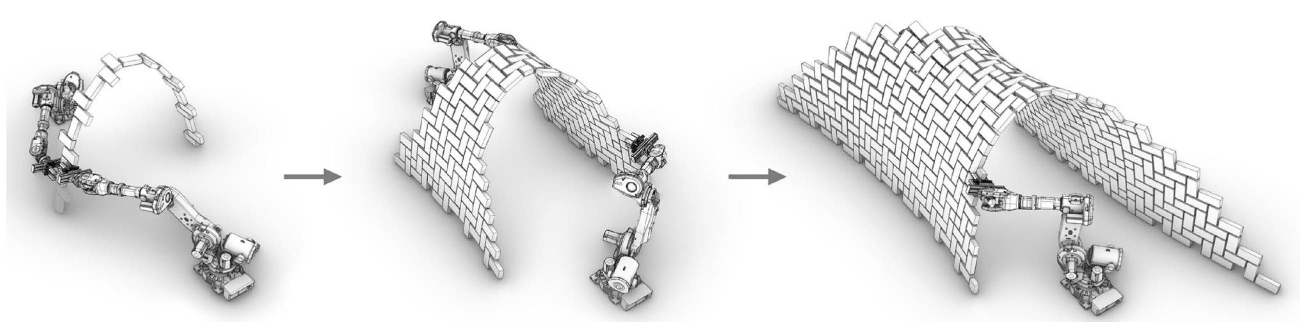


Fig. 2 Cooperative assembly method. First phase: the middle arch is built by alternating the robots used to place and then support the structure. Second phase: the construction is continued on either side of the middle arch

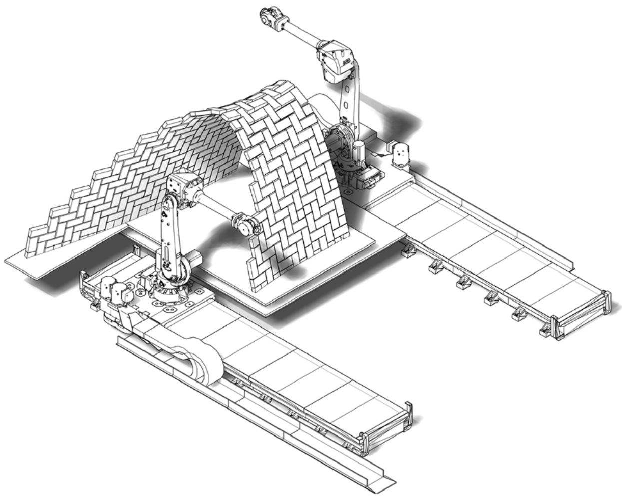


Fig. 3 Robotic fabrication setup

reachability with regards to position and orientation and (2) collision-free placement of bricks.

The first criteria is based on working within the resulting geometric design space, which required that the height of the middle arch be limited to 2 m but allowed for taller areas closer to each robot (up to 3.5 m). This is because the robots have a greater range of motion in this area.

The second criteria are based on the robotic movement paths. Each brick has to be maneuvered from a fixed pickup location to its final position in space while avoiding collisions between: the two robots, the robot and the foundation connections, the robot and the structure itself. To avoid collisions, we analysed the robotic paths for fifteen bricks at critical edge locations and traced the paths of both the end-effector and the robotic arm's elbow joint. The result showed a high collision risk between the robot elbow and the opposite area of the vault. For this reason, the design was adjusted from a shape based on line symmetry to one based on rotational symmetry by removing parts of the structure that lie in the collision volume of either robot's elbow (see Fig. 4).

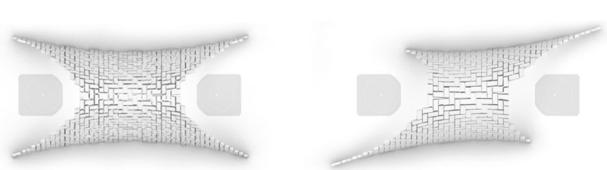


Fig. 4 Original geometry based on line symmetry (left) and adjusted geometry based on rotational symmetry (right)

5 Fabrication

5.1 Material

The prototype that was built represents a 3.3 × 2.6 × 2.0 m section of the final vault structure that will be built as part of the Anatomy of a Structure Exhibit hosted by SOM in London (Parascho et al. 2021). This section consists of 265 bricks (233 full bricks and 32 half bricks), which resulted in 675 brick-to-brick and 40 foundation connections. New bricks were manually placed at four predetermined locations around the build area and were then picked up and placed with pneumatic grippers mounted on the robot arms.

We chose glass bricks for this project because they are similar in density to traditional masonry units, while still possessing a novel aesthetic that conveys a sense of contrast between their physical heaviness and visual transparency. After experimenting with both cut-to-shape recycled glass and cast clear glass bricks, the latter was selected due to superior structural performance and aesthetic effect. Since a standard concrete mix (i.e., normal density) has a similar density to glass—approximately 2400 kg/m^3—concrete bricks are used interchangeably with glass bricks in this prototype due to higher availability.

All full-sized bricks are standardised unit blocks with identical dimensions of 246 × 116 × 53 mm. Using standardised bricks avoids field cutting complex brick shapes, and is cost-effective. Occasionally, half-sized bricks are adopted to minimize overall gap sizes in tessellation.

The setting time for traditional mortar is relatively high. Therefore, studies were performed on various substitute materials (e.g., double-sided tape, reusable Nano Gel Tape, silicone-based glues, epoxy putty etc.), to be used for the connection (see Fig. 5) between the individual glass or concrete bricks. The primary requirement was that this connection material is fast setting and rigid, with enough tensile capacity to hold a brick in place in the temporary construction condition. The material also needed enough flexibility during placement to negotiate variations in the gap sizes between the bricks, which occur naturally when

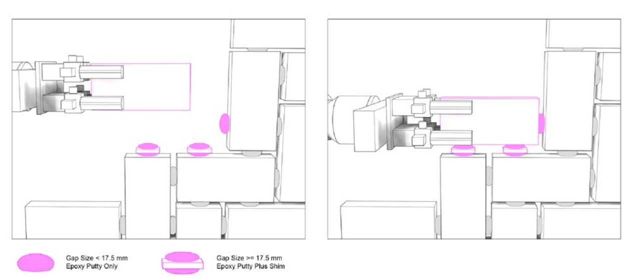


Fig. 5 Connections formed with quick-setting epoxy putty

tessellating a curved surface, and from material and fabrication tolerances. For ease of construction, the connection material needed to be adjustable in real-time to fit these various gap conditions, rather than having a unique connector prefabricated for each gap. Ultimately, the material that best matched all these requirements was the epoxy putty, a multipurpose sealing, patching and mending compound, available in three different brands (Oatey Fix-It, PIG, and PC_Pool). The selected epoxy putty has a handling time of 3–5 min and hardened within 15 min. In addition, our tests showed that it adheres well to both glass and concrete blocks and wooden shims. As a maximum, the self-weight of up to five glass bricks could be cantilevered out and supported by a single epoxy putty connection.

The glass vault is supported at the base by prefabricated custom foundation pieces, which are manually placed and screwed into the base platform after the first brick of a new layer is in position. The foundation pieces are placed sequentially during the construction process, instead of being preassembled, to accommodate tolerances resulting from the robotic setup, and to avoid collisions during the placement of the first bricks in a new layer.

We conducted a series of tests to determine the best gripping surface to use on the pneumatic gripper to allow the robot to firmly grasp and hold a glass brick without scratching its polished surface. A textured rubber surface yielded the best results (i.e., ease of installation and adequate friction to support a maximum weight of 60 kg), exceeding other tested systems such as: uniform silicon mats, patterned silicon mats, and grit sandpaper.

5.2 Brick placement sequence

The design of the construction sequence takes into account the temporary stability of the neighbouring brick assembly (i.e., local stability). At the same time, the global stability of the structure also had to be maintained, while ensuring that each brick could be placed safely—following the planned brick tessellation and avoiding collision and reachability issues. To achieve this, the sequence was calculated considering both a local and global set of rules.

On a global level, the model is divided into nine subsections (see Fig. 6), ensuring that a newly placed brick is connected to the existing structure at a minimum of two discrete points (except for the construction of the middle arch, which follows a specific sequence described in Sect. 5.4). On a local level, the brick sequencing obeys the following two principles:

1. “Stepping” diagonally along the surface of the vault so that the added self-weight is efficiently transferred to the foundations (see Fig. 7)

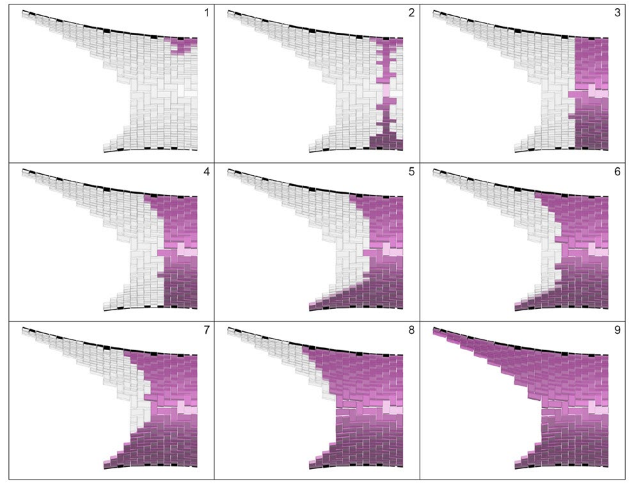


Fig. 6 Building sequence (left–right, top–bottom)

2. Avoiding inserting a new brick into gaps with existing bricks on all three sides, since this limits the space for epoxy adjustment

Placing the bricks diagonally towards a corner with connections at two sides is the preferred approach movement. The construction sequence is not a mirror image between the two sides of construction because the vault has rotational rather than line symmetry. When placing bricks, the other robot is holding the shell from the opposite side for extra support and stability.

5.3 Path planning

The robotic path used to place each brick can be divided into three sections (see Fig. 8): (1) a discrete pickup action; (2) an in-between path through an optional fixed transition pose between pickup and final brick position, which adds predictability of movement and reduce chances of collision; and (3) a parametrically defined path near the final brick position, which consists of the insertion movement. In addition, a small drawing-out movement is programmed before each brick fit-in step, to allow the human worker enough time and space to apply the epoxy putty for each connection.

The path planning algorithm first selects the closest pickup station based on the new brick’s final location. Then the path for brick insertion and gripper withdrawal is generated parametrically. At the insertion stage, the direction of the gripper movement—whether perpendicularly or diagonally towards the neighbouring bricks in the structure—is chosen based on the local geometric context (i.e., avoiding collisions and facilitating the placement of connection epoxy).

The location of the pickup station was chosen to minimise potential collisions between the robotic arms and

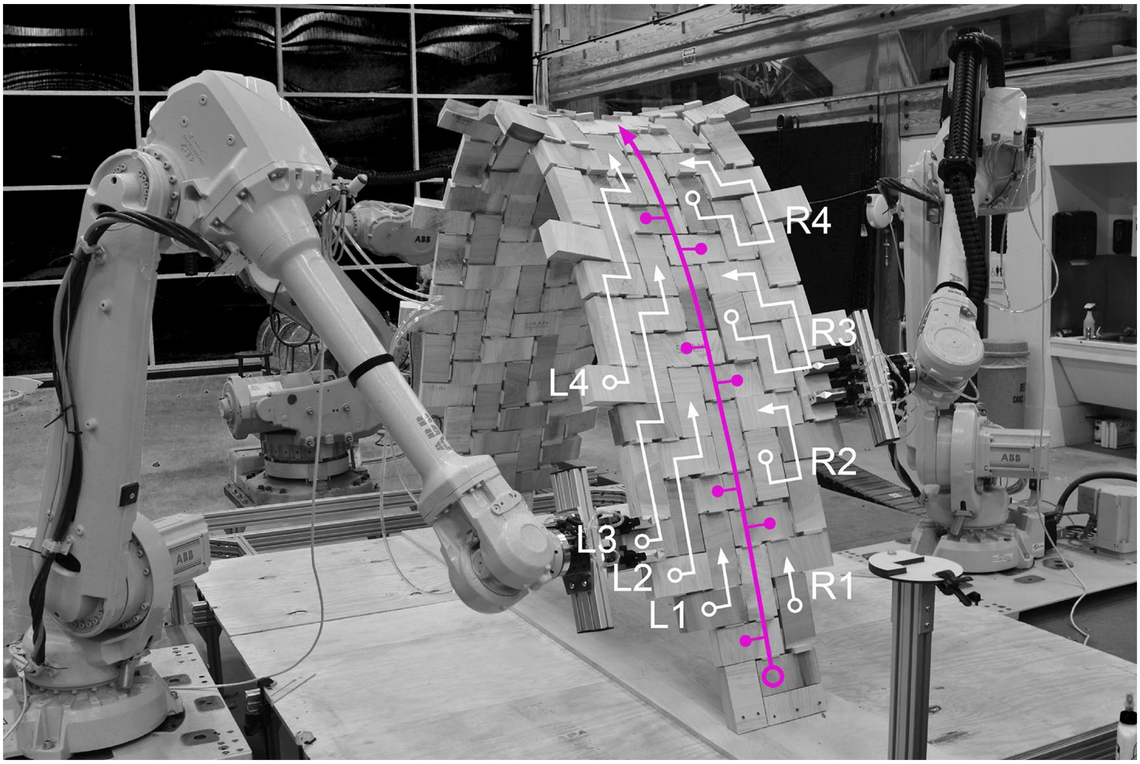


Fig. 7 Vault is built up in steps, such that every brick is supported on two sides when placed by the robot

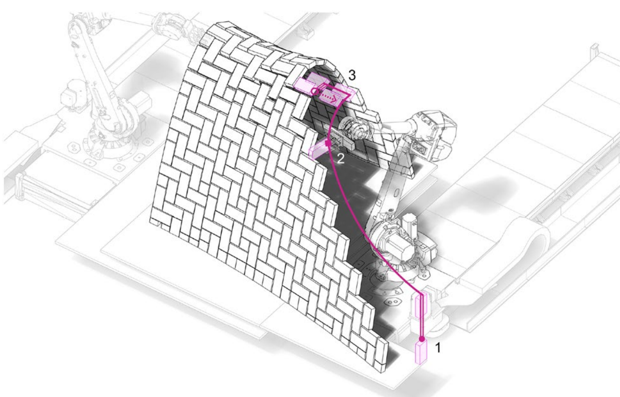


Fig. 8 Typical robotic placement sequence for a single brick

the built portion of the vault during the placement steps. A wooden jig matching the brick's footprint was fixed to the pickup station as a reference to ensure that every new brick is positioned in the exact same location for the robot to grip. Although the bricks were always manually placed in the same orientation at the pickup location, the robots are programmed to pick up the bricks in one of five different ways based on the destination brick's orientation and size (see Fig. 9). The variations in the gripper position accounted for special cases where bricks could not be placed with the initial gripper position and orientation due to collisions or reachability issues. The protruding fasteners (on one side of the grippers only) also influenced the pickup orientation—in certain tight locations, there was a risk of these nodes contacting the adjacent bricks.

5.4 Middle arch fabrication

The middle arch was built sequentially, following a cooperative assembly method. The robots were used to provide support during construction (see Fig. 10) before the arch was completed (i.e., reached the other end support) and became structurally self-supporting.

The main challenge was supporting the self-weight of the arch as it was being constructed. The forces acting on the gripper and robot arm supporting the arch in the temporary condition continuously increase as more bricks are added. This support force should not exceed the payload of the robotic arm, which was 40 kg at maximum speed and 60 kg if ABB's motion supervision option is deactivated. One glass brick weighed 3.66 kg, so to keep an adequate margin of safety, we decided that a robot should not support a weight equivalent to more than ten bricks (i.e., 36.6 kg). Therefore, we adjusted the construction sequence, and prebuilt the bottom section of the arch at one end. As a result, the portion of the arch, starting from the other end, only

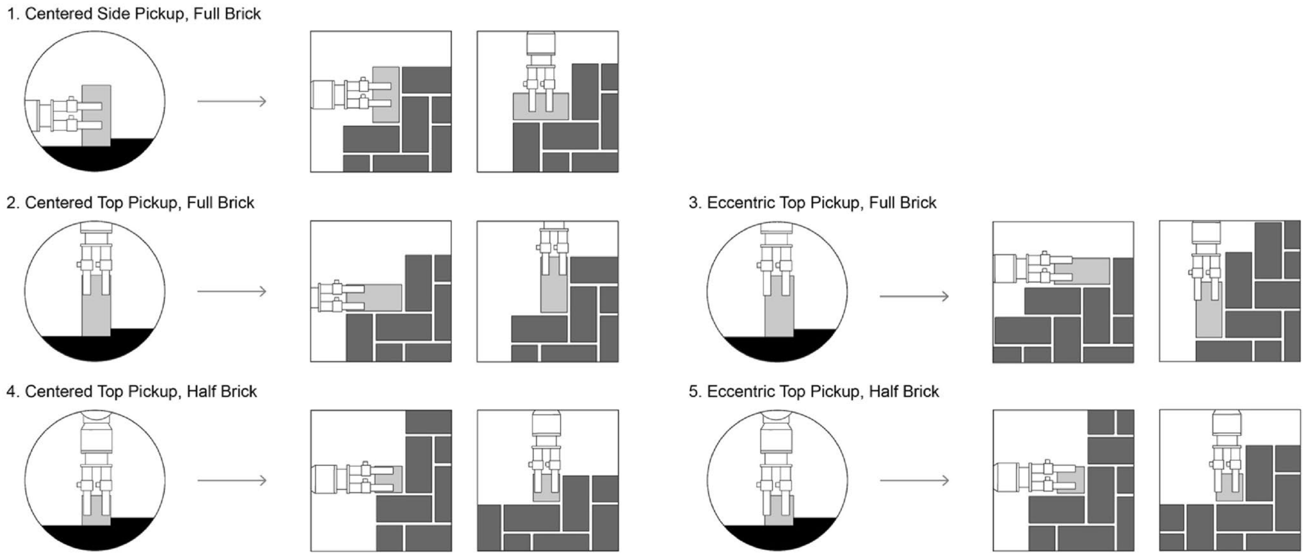
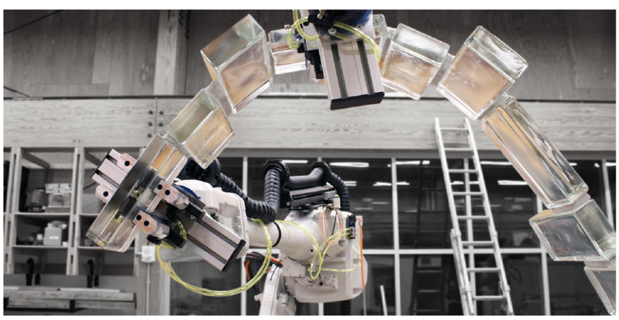
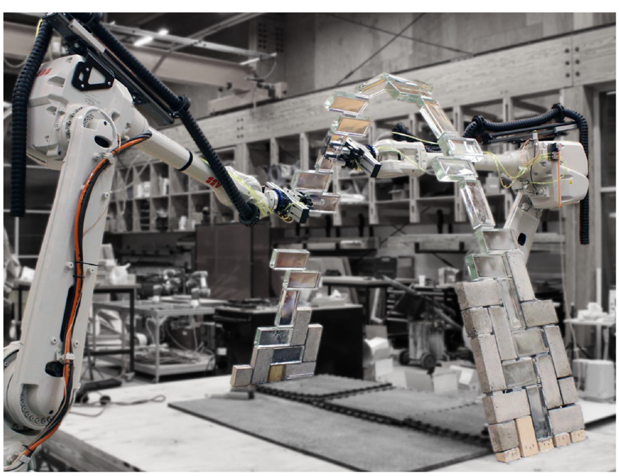


Fig. 9 Gripper position options for pickup and placement



(a) Passing the crown of the arch. One robot supports the arch at the highest point of the arch to provide stability.



(b) Approaching the end support of the arch. Additional bricks close to the base provide lateral support.

Fig. 10 Middle arch construction

needed to be a total of 19 bricks. This self-weight was split evenly between the foundation and the robot gripper, which resulted in a maximum support weight below the ten-brick threshold we established. In addition, we ensured that the gripper's centre-point (i.e. where it holds the brick) was as close to the thrust line of the arch as possible, which reduced the out-of-plane twisting that would result from this load eccentricity.

We considered three alternative methods (see Fig. 11) for building the middle arch and settled on the "Cantilever Method" repetitive three-brick pattern (i.e., horizontal–horizontal—vertical) between the two robots (i.e., left and right). Each robot first cantilevers two horizontal bricks out (i.e., H1R', H2R', H1L', and H2L' in Fig. 11) before placing the vertical brick (i.e., V3R and V3L in Fig. 11), at which point the weight switch happens (i.e., robot 1 goes from placing bricks to supporting the structure). This approach ensures that one robot always has a hold on the structure at a point close to the thrust line of the arch as the weight is shifted from one robot to the other.

Due to the slenderness of the middle arch, we identified a risk for it to be destabilised by lateral forces that occur either during the placement of a new brick or from eccentricities due to construction tolerances. In addition, minor shaking occurs when a load-bearing robot arm releases its grip on the arch, handing over the weight to the other one. This unwanted movement can be limited to below 5 mm (an acceptable value), when releasing the maximum weight of 40 kg, by regulating the speed of the gripper opening with flow control valves. We also modified the construction sequence to add a total of 16 bricks around the support at either end of the middle arch to increase

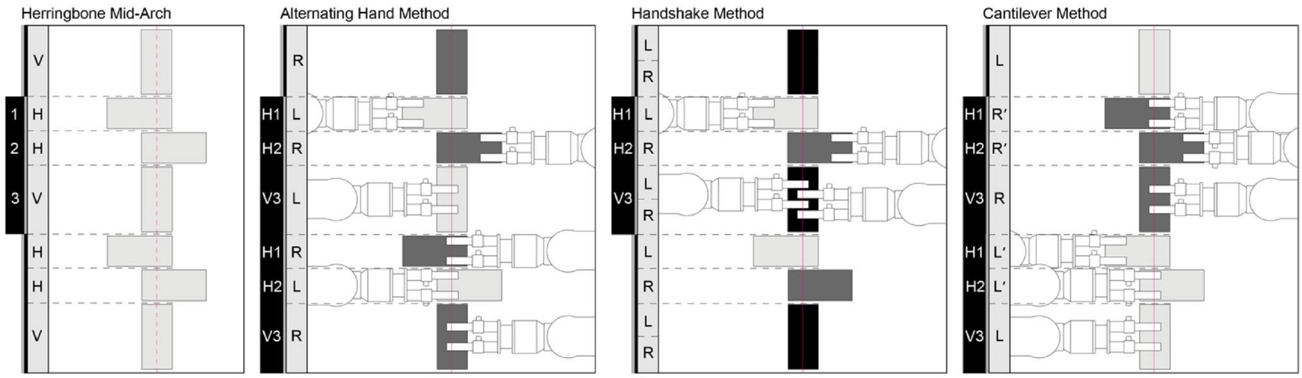


Fig. 11 Middle arch geometry and sequencing methods

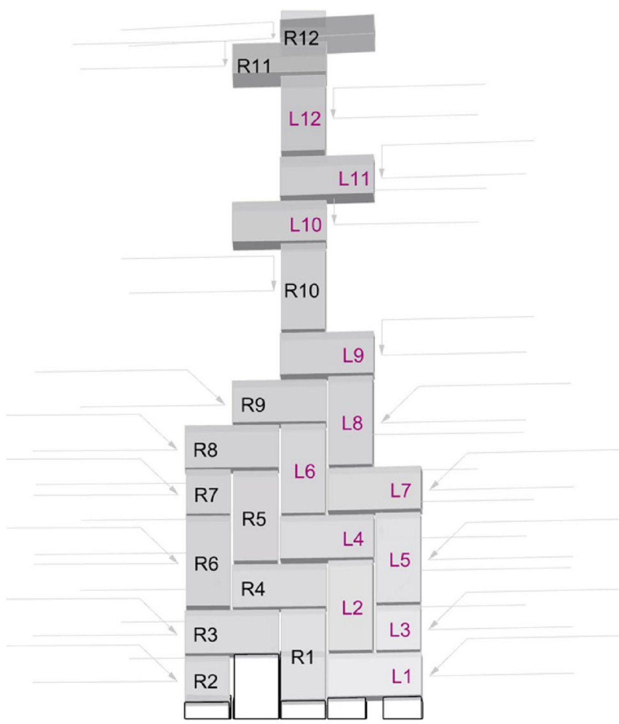


Fig. 12 Middle arch base sequence (*R* right robot, *L* left robot), arrows indicate the insertion path

lateral stability. However, we ensured that these bricks are inserted into the assembly sequence (see Fig. 12) such that they combine both the middle arch sequence and the double-sided-support sequence of the sides (i.e., phases 1 and 2 as defined in Sect. 3.1). This means that one robot was always supporting the middle arch, even when the other robot was adding the lateral support bricks. In general, we also avoided robotic handshakes (switching on same brick, refer to Fig. 12) since this move results in dynamic forces when the gripper opens that increase the risk of destabilising the arch.

5.5 Vault extension

Once the middle arch was completed, we extended the vault outwards with the middle arch serving as a backbone. The most challenging aspect of this phase was planning the construction sequence to keep the vault balanced and structurally stable in the various temporary states. With respect to assembly, selecting the correct robotic arm movements was critical to avoid collisions with the built portion of the existing structure. With this in mind, we alternated building “chunks” of about 20–30 bricks on the front or back side of the vault, before switching to building on the opposite side. In each of these chunks the bricks were also placed on the left and right side of the middle arch. In this way, we managed to uniformly build the structure without introducing unnecessary unbalanced forces in the temporary condition. This strategy also helped ensure that the movement of the robots did not get constrained by one side of the vault extending into the maneuvering space required to build the other side.

5.6 Execution

The total assembly time for the 265-brick prototype (see Fig. 13) was two weeks, with a workforce of two to four people. To fill and secure the connection between bricks, 960 ounces of epoxy putty was used. For the fabrication of the middle arch, approx. 25 min were needed to secure each brick, and 12–15 min per brick for the rest of the vault. During the lateral extension phase, the switch between robot driving/placing and waiting for the epoxy to set for the other robot created a balanced back and forth rhythm.

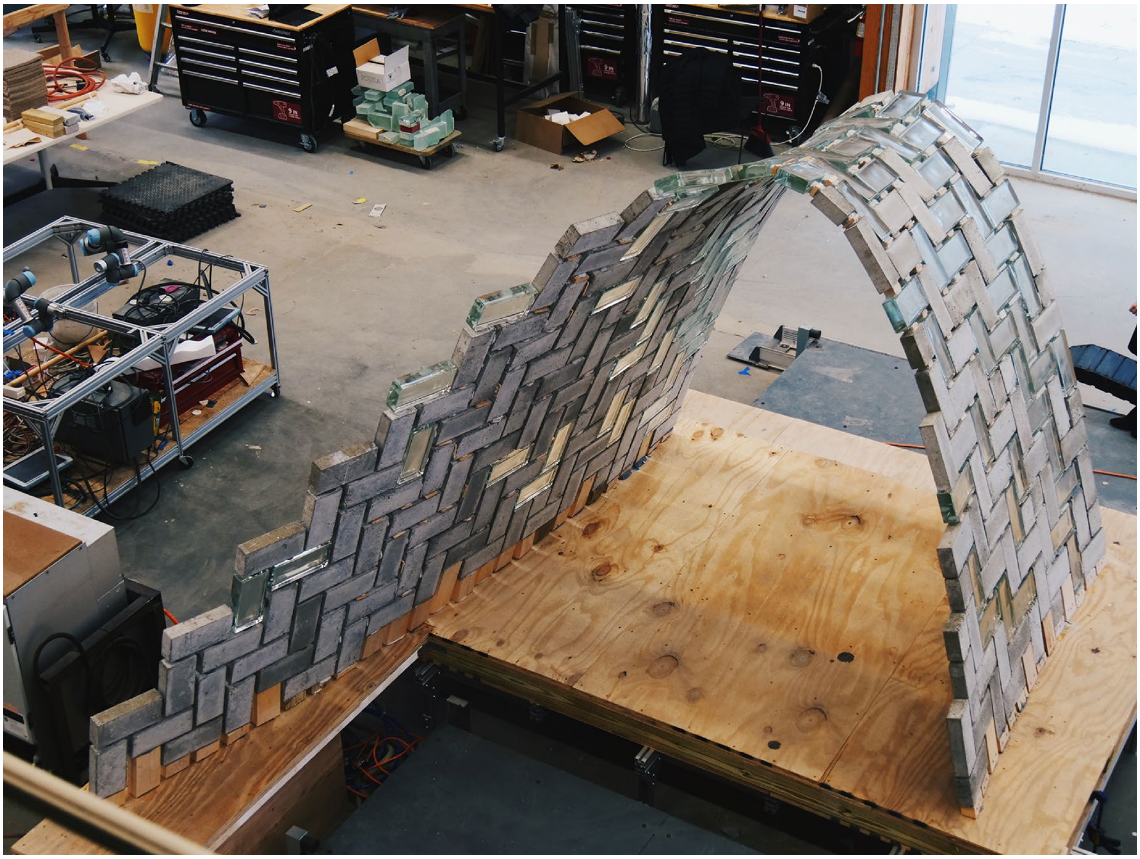


Fig. 13 Completed prototype brick vault

6 Conclusion

6.1 Results

We have shown that cooperative robotic assembly methods can be applied to the construction of a spanning structure, which is built without temporary falsework. Where traditional manufacturing techniques would require geometric guides, this project shows how we can instead leverage the robots' precision to place bricks accurately in bespoke orientations. Overall, the project has pushed the state of the art in cooperative robotic assembly of masonry structures forward by breaking from the traditional vertical construction paradigm. The resulting method allows for the materialization of form-found doubly-curved vault geometries that are designed to efficiently carry applied loads through compression-only membrane forces.

We developed strategies for sequencing, path-planning, and computing final brick positions based on fabrication constraints for a structurally functional and buildable shell geometry. Finally, we applied the developed techniques to build a large-scale prototype of 256 bricks using a collaborative robotic fabrication framework (i.e., two robots working together). Throughout the development stage, we had to ensure the adaptability and transferability of our techniques to other robotic setups, as brick shell construction can only be performed on site. Thus, we allowed for local robotic setups (i.e., varying the structural scale, robots, and construction material) to be easily adapted to our proposed methods. This will be further demonstrated in the next iteration of the project, which will involve the construction of a larger glass brick shell at the Anatomy of a Structure Exhibit hosted by SOM in London [14], utilising robots mounted on site.

6.2 Outlook

Future developments will focus on the adaptability of the developed techniques for sequencing and path-planning for new geometries. We want to consider multi-robotic setups with more than two robots and robots of different dimensions to allow more flexibility, and adjust our design methods to automatically generate brick shell geometries that take into account both structural and fabrication constraints. Due to the complexity of these two types of constraints, further research on algorithms for design generation is needed. To achieve a seamless and fast design environment, research in automating the robotic path-planning process is required to allow for a full integration into the design process. Also, expanding the mobility of the robots (i.e., by employing robots on track or fully mobile), would allow us to reconsider the structural scale limitations inherent with robots mounted on a fixed base. Ultimately, we want to achieve a fully informed non-sequential design and fabrication process that can generate, discretise, and robotically assemble load-bearing shell structures.

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