Manufacturing Methodology for Precast Concrete Tiles with Morphing Shapes

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Abstract. This study presents a novel, sustainable method for producing diverse concrete tiles with a reusable mould, addressing the waste issue associated with traditional tile moulds. Our digital manufacturing system, composed of a Rhino Grasshopper-based design system and an electric actuator-based kinetic mechanism, simplifies the construction process and lowers costs. The effectiveness of this method is showcased through six case studies, demonstrating its adaptability in diverse morphing tile designs, including the reinterpretation of traditional Islamic pattern. This approach opens new possibilities for the cost-effective, sustainable, and versatile use of concrete tiles in architecture.

Keywords: Digital Fabrication, Additive Manufacturing, Actuated Mould, Morph, Tessellation Tiles.

1 Introduction

In contemporary construction, concrete moulds, particularly for concrete tile fabrication, are ubiquitously employed (Akbari et al., 2003; Durbin, 2006). However, each tile mould is restricted to one type of tile. It generates substantial waste and limits the implementation of morph designs, which require a multitude of unique shapes (Đurašinović and Jovanović, 2020; Yun et al., 2022). Traditional tile manufacturing processes rely heavily on handcrafting to meet design variability, leading to challenges in the expenditure of significant labor, materials, and funds (Giorgini, 2001; Tsantini et al., 2017).

Many studies used flexible moulds to produce concrete elements with different shapes (Jepsen et al., 2010; Schipper et al., 2015). Nevertheless, these systems are not suitable for small size concrete tiles. In response to this challenge, this research introduces a manufacturing methodology that leverages actuated concrete moulds for making morphing concrete tiles. This innovative methodology encompasses design algorithms based on Rhino Grasshopper and a hardware system driven by Arduino and electronic actuators. This methodology can change the shape of the produced tile by precisely tilting the mould, making it possible to make multiple shapes of tiles using a single mould. It not only minimizes mould waste but also enriches the usage of morphing design in tile production.

This paper begins by reviewing representative works related to concrete moulds and actuated mould systems. This is followed by an exploration of the system design of the proposed manufacturing methodology, split into hardware and software components. The construction process of the methodology is then elaborated upon. Six case studies are subsequently presented to substantiate the method's feasibility. To conclude, the paper discusses the limitations of this research and anticipates future directions for refinement and expansion.

2 Related Work

With the surge in demand for concrete tiles in both interior and exterior decoration, there has been a notable industry-wide shift toward the use of reusable precast concrete tiles (Kiss-Balázs, 1986). This widespread adoption serves as an effective strategy to reduce mould waste before the advent of actuated mould systems. For example, Samuel Wright, in 1830, received a patent for inlaid tile manufacturing, creating a method for tile mass-production (Durbin, 2006). In addition, John Earley enhanced interior finishes by utilizing reusable moulds to create repeating elements, as seen in the Shrine of the Sacred Heart, Washington, DC. (Armbruster, 2019). Similarly, F. L. Wright employed intricately embossed tiles for the facade of the Millard House (Heinz, 2016).

Most studies on actuated moulds have adopted the "pin-table" method. Here, linear actuators control each pin's position, thereby modifying the mould's form (Baghi et al., 2022). In 1961, the first manually configured pin mould with a high resolution was granted a patent (Hicks, 1959; Peters, 2013). Piano proposed actuated moulds using a grid of actuators on a flexible surface (Piano, 1969). Whitacre then introduced a device using Numerical Control to cut rods for manual mould assembly (Whitacre, 1971).

In recent years, Jepsen et al. utilized digital control to shape a double-curved surface from a digital computer-aided design model (Jepsen et al., 2010). Furthermore, Schipper et al. developed a flexible mould system for curved architectural components (Schipper et al., 2015). Van der Weijst designed an actuated mould for the purpose of casting glass voussoirs with diverse geometries (van der Weijst, 2019). Đurašinović and Jovanović cast morphing triangular plaster tiles, using a mould with replaceable walls (Đurašinović and Jovanović, 2020). Baghi et al. presented a novel method to create diverse concrete joints (Baghi et al., 2022). They combined flexible pressure-enduring tubes with a rigid mechanism to address non-standard concrete element production.

Despite the growing research on using flexible moulds to produce diverse concrete elements, a noticeable gap remains in their application to smaller concrete tiles. The current systems are complex and often involve high costs, making them impractical for small scale productions. Furthermore, the domain of using actuated moulds to fabricate morphing concrete tiles is relatively unexplored. This underlines an untapped opportunity in the field to develop more economical, efficient methods for manufacturing morphing concrete tiles.

3 System Design

The manufacturing process employs an integrated system that combines an actuated mould mechanism with a design system rooted in the Rhino Grasshopper platform. This manufacturing system operates on the principle of using a single mould to produce tiles of diverse shapes by tilting the mould and adjusting the concrete volume (shown in Fig. 1).

3.1 Hardware Design

The hardware system is composed of a mould platform, an actuation system, and a control system. The system is powered by an external 12V 5A source. In addition, transparent acrylic boards and 3D printed PLA elements were used to make the frame of the system, taking into account the needs of maintenance and fixation.

Mould Platform

The mould platform is composed of a 2mm-thick iron plate, tile moulds, and fixtures. It is designed to securely hold moulds at any angle and position (shown in Fig. 2). Tests showed that a 2mm plate was optimal, as a 1mm-thick plate struggled to maintain horizontality and a 3mm plate was too heavy, causing it to slide down. Additionally, the evenly distributed small holes on the iron plate allow for flexible mould placement.

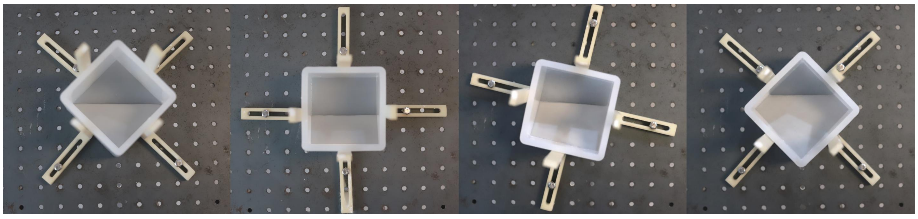

Figure 1. Tiles with different shapes produced by one mould.

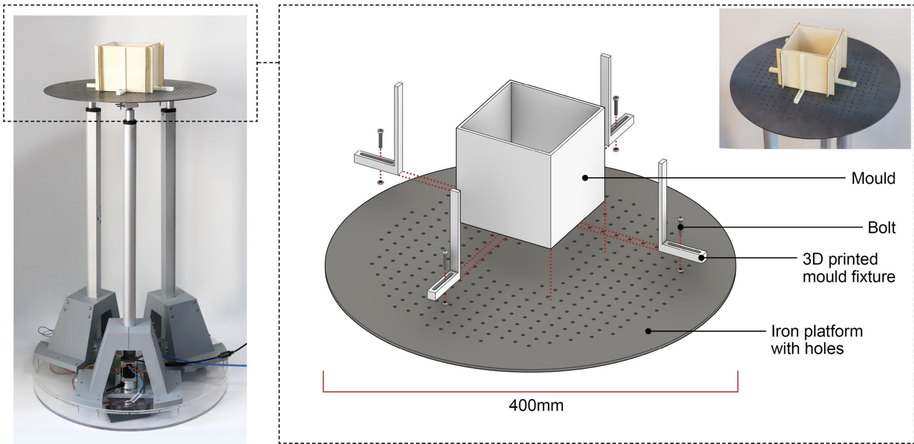

Figure 2. Mould platform diagram.

Actuation System

The actuation system incorporates electric actuators, drivers, and magnet nodes (shown in Fig. 3). These actuators aim to achieve predetermined mould platform tilt angles through extension. To ensure a connection with the platform during movement, a magnet node is positioned at the actuator-platform junction to permit relative displacement. The actuators form an equilateral triangle with a 200mm side length, offer three degrees of freedom, enabling various tilt angles in three-dimensional space. The choice of 500mm electric actuators was based on cost-effectiveness and the ability to achieve desired tilt angles, with the achievable tilt angle (relative to the horizontal plane) ranging from 0° to 70.9°. The independent operation of each actuator is managed via the Arduino Integrated Development Environment (IDE).

Control System

The control system components include an Arduino UNO R3 development board and a computer (shown in Fig. 4). The Arduino board acts as an intermediary between the computer and the motor driver, sending the processed digital signals to the motor drivers. Eventually, the electric actuator moves as described in the code.

3.2 Algorithm Design

The design algorithm for the manufacturing methodology is based on Rhino Grasshopper (shown in Fig. 5). The Grasshopper script can accurately calculates the tile shape under any given mould platform tilt angle and concrete volume. In this way, the user can design the tile shape by adjusting tilt angle and concrete volume in Grasshopper. After designing the tile shape, the electric actuator movement parameter calculated in Grasshopper is imported into the Arduino IDE. As a result, the mould platform tilts to the exact desired angle.

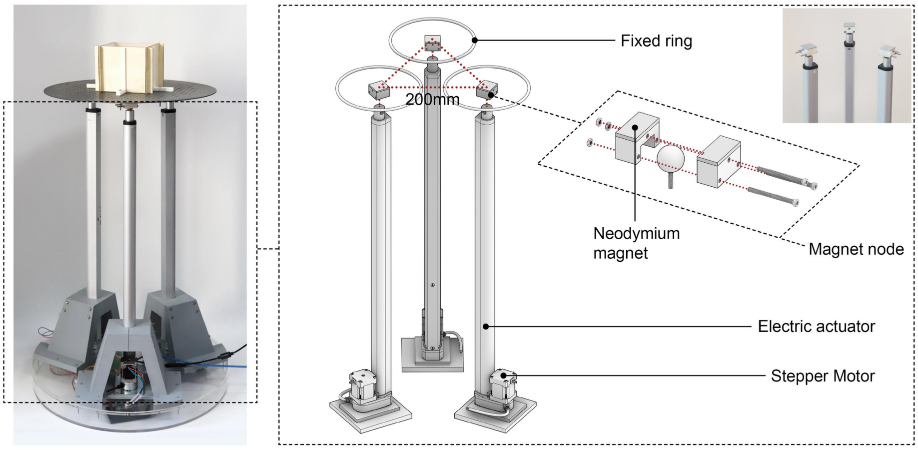

Figure 3. Actuation system diagram.

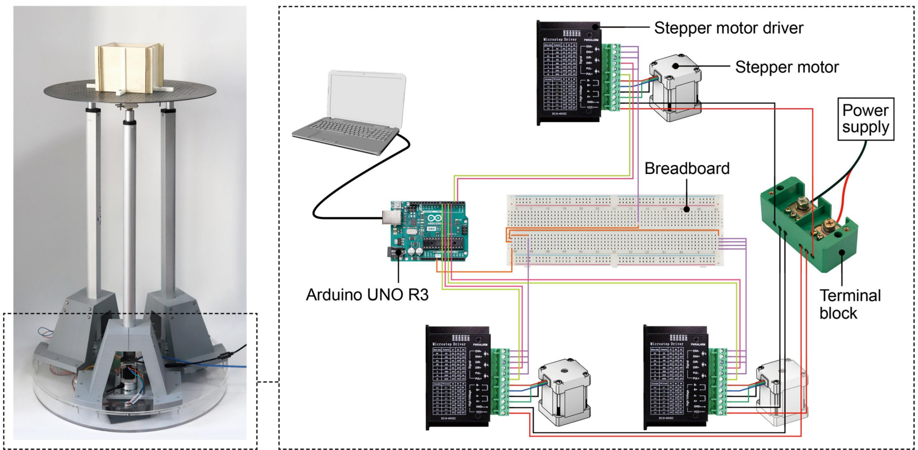

Figure 4. Control system connection diagram.

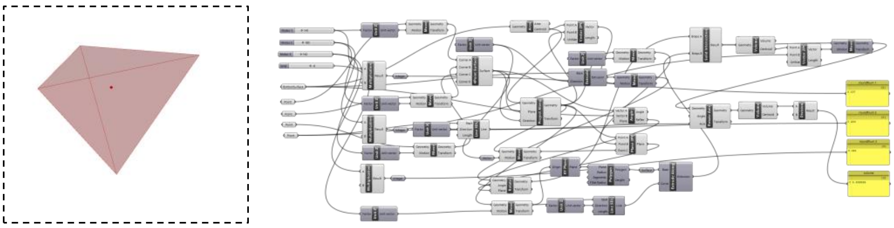

Figure 5. Grasshopper code and shape simulation.

4 Construction Process

Various materials were experimented with during prototyping, including quick-drying white cement and quick-drying high-hardness cement. Different ratios of cement, water, and aggregate were tested. A low water-to-cement ratio resulted in a thick concrete with arc-shaped edges, while a high water-to-cement ratio prolonged the time to solidify and reduced manufacturing efficiency. Ratio 1:3:0.5:0.5 (shown in Table 1) was chosen for prototyping considering its fluidity and solidification time.

The construction process consists of four main steps (shown in Fig. 6): (1) Pattern Design: Users first design a two-dimensional tile pattern, considering cultural or formal elements. (2) Shape Design: Based on the pattern, the mould's shape is identified. Users then employ Rhino Grasshopper to design the 3D tile shape and generate essential construction parameters, including the length of actuator movements and the required concrete volume for each tile. (3) System Operation: The length for each actuator movement is input into the Arduino IDE. Upon uploading the command, the actuators elevate and halt automatically. (4) Concrete Casting: Users secure the mould on the platform and pour the concrete mixture into the corresponding mould.

This process offers high design flexibility and a low entry threshold, demonstrating the system's generalization capabilities. Additionally, the construction process optimizes productivity by grouping tiles with identical tilt angles for simultaneous manufacturing on the mould platform.

Table 1. Material ratio comparison

Cement Type	**Quick-drying white cement**			**Quick-drying high hardness cement**		
Water:cement:sand :gravel	1:5:1:1	1:5:0.5 :0.5	1:6:0.5 :0.5	1:3:1:1	1:3:0.5 :0.5	1:4:0.5 :0.5
Fluidity	++	+++	++	++++	+++++	++++
Solidification time	1.3h	1.2h	1h	1.2h	1.1h	1h

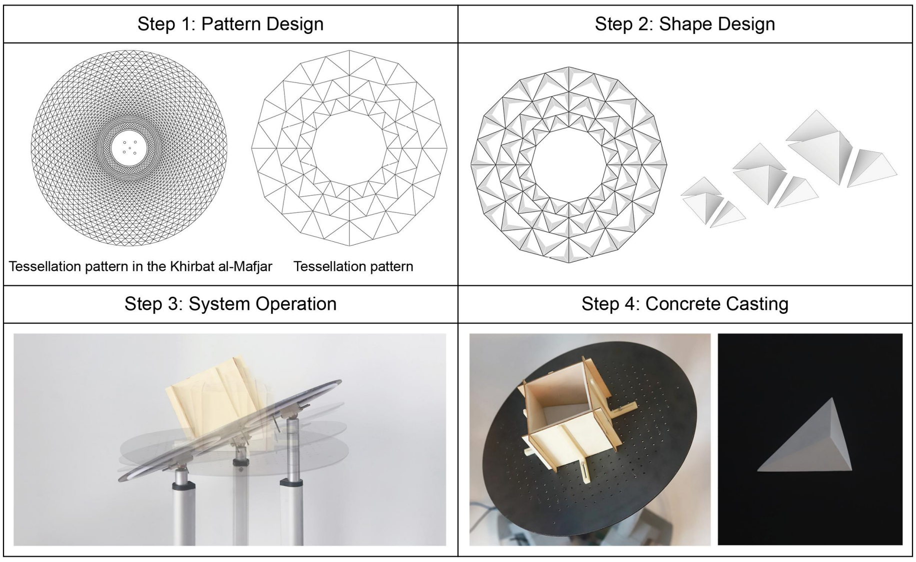

Figure 6. Construction steps of the manufacturing methodology.

5 Case Study

Case study is an essential methodology in architectural research (Adewumi et al., 2020). It offers a structured approach to exploring empirical topics based on predetermined procedures (Yin, 2009). In the architecture field, historical cases, design processes, models, and the researcher's own creative activities tend to be the cases of case studies (Nnaemeka, 2015; Adewumi et al., 2020). In this study, we conducted six cases to illustrate the feasibility of the manufacturing system by showing diverse tiles produced by it.

Parameters	Total Length	Total Width	Tile Length	Tile Width	Tile Height	Tile Volume	Angle
	420mm	420mm	37-82mm	24-54mm	12-27mm	1.8-20ml	42°

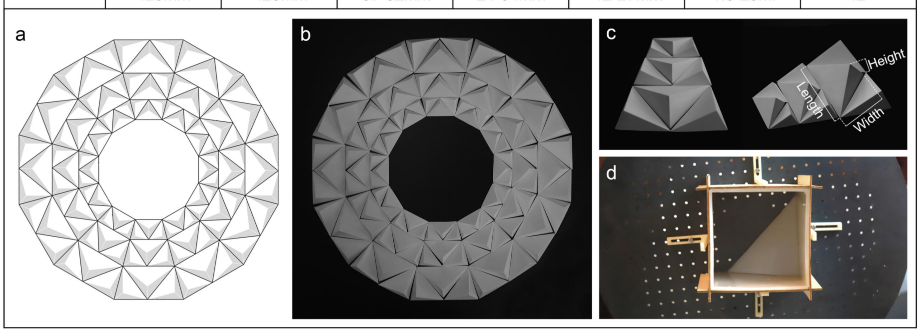

Figure 7. Parameters and photos of case 1. (a) tessellation prototype of case 1. (b,c) photos of concrete tiles. (d) fabrication process of case 1.

5.1 Case 1

Case 1 presents morphing concrete tiles produced by this manufacturing system with a square mould. The tessellation prototype is derived from the tessellation pattern in the floor of Khirbat al-Mafjar. This pattern consists of 12 repeating modules (shown in Fig. 7b), with 9 tiles in each module (shown in Fig. 7c).

5.2 Case 2

Case 2 highlights a tessellation pattern inspired by classical rectangle tessellation. This staggered design is reminiscent of patterns commonly found in brick walls. By adjusting the length of the rectangle, the pattern exhibits a morphing tessellation. Additionally, by positioning multiple identical moulds on

Parameters	Total Length	Total Width	Tile Length	Tile Width	Tile Height	Tile Volume	Angle
	200mm	156mm	50mm	9-30mm	4.5-15mm	1-11.2ml	45°

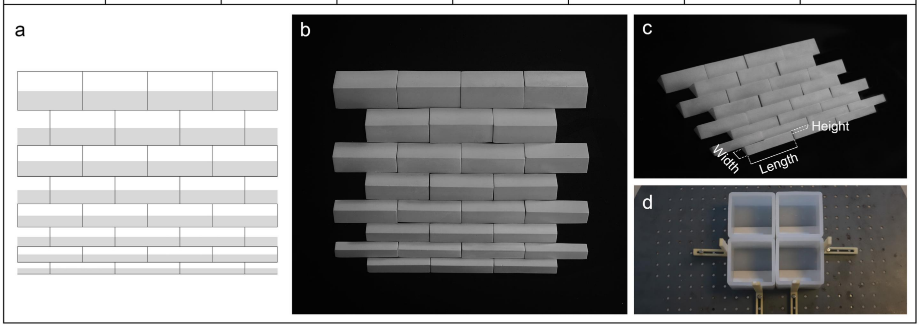

Figure 8. Parameters and photos of case 2. (a) tessellation prototype of case 2. (b,c) photos of concrete tiles. (d) fabrication process of case 2.

Parameters	Total Length	Total Width	Tile Length	Tile Width	Tile Height	Tile Volume	Angle
	200mm	156mm	50mm	9-30mm	4.4-14.9mm	1-10.8ml	36-45°

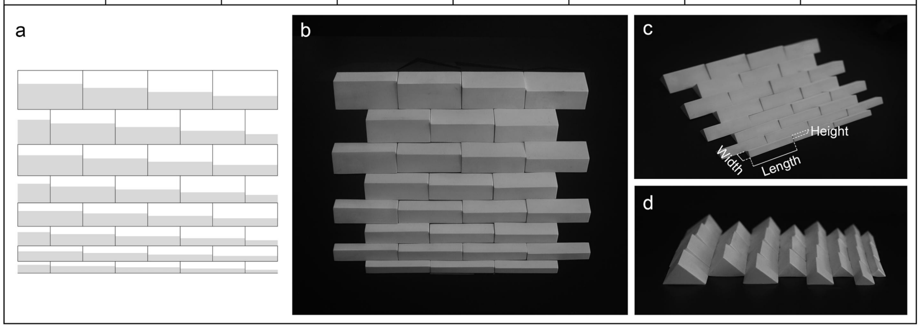

Figure 9. Parameters and photos of case 3. (a) tessellation prototype of case 3. (b-d) photos of concrete tiles.

the mould platform, several tiles can be crafted simultaneously, significantly enhancing the fabrication efficiency (shown in Fig. 8d).

5.3 Case 3

Case 3 employs the same tessellation prototype as Case 2. By subtly altering the position and height of one triangular prism edge, Case 3 introduces richer morphing details in its 3D configuration (shown in Fig. 9). This adjustment makes the design more intricate and dynamic in its spatial presentation.

5.4 Case 4

While Case 4 employs the same manufacturing parameters as Case 2, it adopts a different tessellation pattern, presenting a rectangle-weave morphing tessellation when viewed from above (shown in Fig. 10).

Parameters	Total Length	Total Width	Tile Length	Tile Width	Tile Height	Tile Volume	Angle
	240mm	233mm	50mm	18-50mm	9-25mm	4-30.5ml	45°

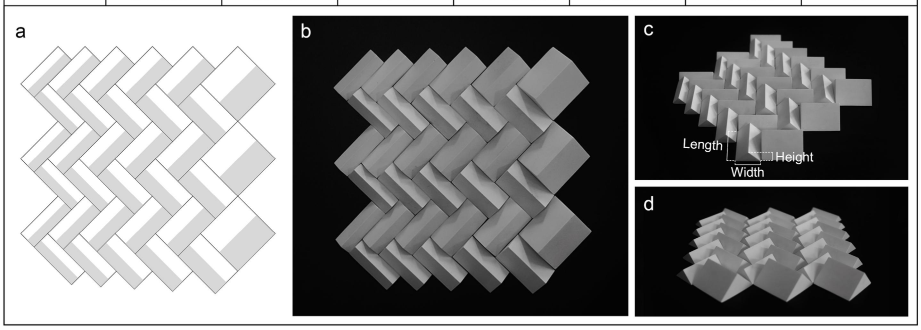

Figure 10. Parameters and photos of case 4. (a) tessellation prototype of case 4. (b-d) photos of concrete tiles.

Parameters	Total Length	Total Width	Tile Length	Tile Width	Tile Height	Tile Volume	Angle
	277mm	240mm	69.3mm	60mm	10-34mm	15.7-53.1ml	8-26°

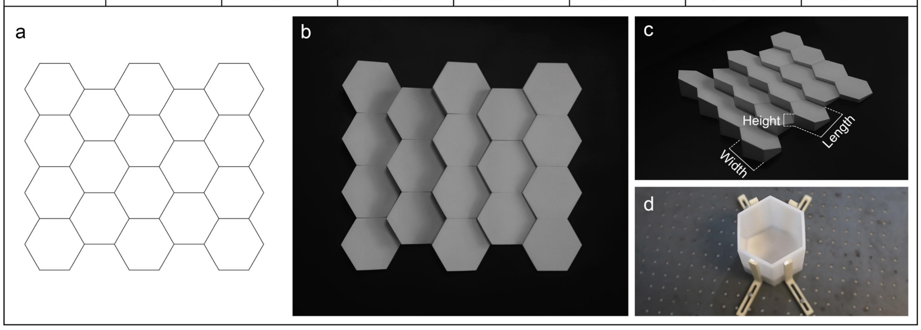

Figure 11. Parameters and photos of case 5. (a) tessellation prototype of case 5. (b,c) photos of concrete tiles. (d) fabrication process of case 5.

Parameters	Total Length	Total Width	Tile Length	Tile Width	Tile Height	Tile Volume	Angle
	280mm	204mm	70mm	30-76mm	6.4-37.4mm	4.6-74.2ml	12-38°

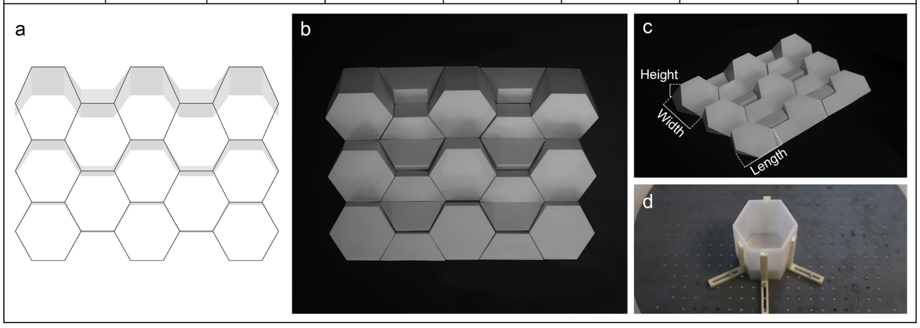

Figure 12. Parameters and photos of case 6. (a) tessellation prototype of case 6. (b,c) photos of concrete tiles. (d) fabrication process of case 6.

5.5 Case 5

Case 5 features a tessellation pattern based on regular hexagonal tiling. By varying the height of the tiles and adjusting the angle of the hexagonal surface, Case 5 achieves a dynamic morphing effect in a 3D space (shown in Fig. 11).

5.6 Case 6

Case 6 introduces a tessellation pattern that enhances the regular hexagonal tiling by incorporating morphing elements. This design allows the distance between two opposite sides of the hexagon to increase progressively (shown in Fig. 12). As a result, irregular hexagons emerge within this morphing tessellation pattern. Without changing the mould, two trapezoids cleverly form the needed hexagon, maintaining a gap-free pattern.

This chapter explores innovative tessellation tiles using a unique manufacturing system. Inspired by historical motifs and classical geometries, the designs transition from simple patterns to intricate 3D configurations. Techniques such as tile height adjustments and trapezoid integrations amplify the designs' versatility. Overall, these cases showcase the system's capability to produce diverse tessellated tiles.

6 Discussion

This research presents a novel tile manufacturing system centered on an actuated mould apparatus, enabling the creation of diverse tile sizes and shapes through a singular mould's tilting. This approach conserves mould materials and signifies a new direction for precast concrete tile, as demonstrated through six case studies. Furthermore, this innovation broadens the application of morphing elements in architecture, forming a platform for future enhancements and potential applications.

While promising, the current system has certain limitations. For instance, the tilt angle of the mould platform is primarily restricted by the rotatable nodes and the platform's surface area. In addition, there are minor inaccuracies when transferring the concrete mixture from the measuring cup to the mould.

In future research, the areas of focus include discovering suitable casting materials and their optimal proportions to increase the system's efficiency. The integration of a pumping mechanism presents another potential advancement, enabling multiple pours and fully automated tile production. Additionally, the design of automatic parameter generation algorithm based on shape demands offers a path for further refining and diversifying the manufacturing process.

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