MASS-CUSTOMIZATION OF INTEGRATED GREEN WALL BUILDING BLOCKS THROUGH CLAY PRINTING FORMWORK

WEISHUN XU[1], CHENXI JIN[2], XIDONG QIAN[3], and ZIHAO JIN[4]
[1,2]*Zhejiang University College of Engineering and Architecture*
[3,4]*The Architectural Design & Research Institute of Zhejiang University Co., Ltd.*
[1]*xuweishun@zju.edu.cn, 0009-0000-4489-7858*
[2]*jinchenxi@zju.edu.cn, 0009-0002-1233-9506*
[3]*584631497@qq.com, 0009-0006-6199-3693*
[4]*archzihaoking@gmail.com, 0009-0003-1709-8569*

Abstract. Fabricating customized green wall modules with 3D clay printing (3DCP) formwork can facilitate integration with building systems such as self-supporting structure while treating stay-in-place clay molds as plant media. However, to realize such designs in real-world construction, further researches are needed to explore pathing strategies to allow for uneven distribution of plant media space and integration with lateral reinforcements. Moreover, measures for mass-customization need to be explored for automated printing path generation and cumulative error control. This research presents a 3DCP-formwork-based design solution for multi-functional green wall building block mass-customization, featuring enlarged, uneven distribution of plant media spaces, and building system integration with modular conduits. Fabrication of distinctive mold components, including plant media spaces, linking paths and boundary molds are automated by pattern-filling path generation algorithms under a discrete framework. A sustainable hybrid formwork setup is introduced to address fabrication speed and calibration between different fabrication procedures. An empirical construction experiment is conducted to validate the proposed methodology in a real-world interior renovation project.

Keywords. 3D Clay Printing, Green Wall, Hybrid Formwork, Multifunctional Building Block, Mass-customization.

1. Introduction

Green walls with living plants can play a key role in building carbon footprint control by providing ecosystem services (Teotónio et al., 2021). Apart from green facades, vertical planting systems are commonly designed as modular plant media (usually soil substance) units attached to an existing structure with extra system requirements (Manso & Castro-Gomes, 2015). Such structural dependence increases materials and construction procedures needed for construction and subsequently carbon footprint.

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Large-scale additive manufacturing, or 3D printing, has brought new perspectives in integrated functionalities in building components including green wall systems (Gosselin et al., 2016). While earlier tests such as BAYAN ECO WALL are largely plastic holders of separate green wall system components(Chahin et al., 2022), recent developments have allowed integration between green wall systems and critical building components such as the building envelope (He et al., 2020).

As a critical method to reduce carbon footprint in concrete building component pre-fabrication through mold recyclability and component self-weight reduction, 3D printed dissolvable formwork may lead to promising applications in multifunctional and self-supporting green wall construction. Compared to directly printing concrete components, 3D printed formwork emphasizes enhanced control over the casting material and easier integration with reinforcements (Jipa & Dillenburger, 2022). In addition, one critical feature of a modular green wall system, the plant media space as a hollow space, is the main advantage of 3D printed dissolvable formworks brought by drastically improved material removability (Leschok & Dillenburger, 2019; Mozaffari et al., 2023). More specifically, the recyclability and removability of 3D clay printing (3DCP) has allowed for the feasibility of using stay-in-place clay mold as plant media in concrete building block fabrication with sustainable formwork (Wang et al., 2020). Later research has proven the feasibility of growing plants on 3D printed clay (Crawford et al., 2022), providing empirical evidence for further application of 3DCP formwork in green wall module fabrication.

However, to adopt 3DCP formwork for self-supporting green wall building blocks into real-world construction, further investigation should be made at two scales. At the scale of individual building blocks, pathing of clay printing should allow for uneven distribution of the planting media based on the different needs of the species. And at the scale of the green wall as a building component, integrated space for larger-scale systems such as lateral bracing or irrigation must be considered to ensure that the wall functions as a part of the entire building. The technique also faces challenges in formwork sustainability and error control for mass-customization, as a modular wall can have multiple serial components (Xu & Huang, 2020).

This paper presents a new design-fabrication methodology for the mass-production of integrated, self-supporting green wall building blocks, addressing the involvement of enlarged, uneven distribution of plant media spaces for root development, as well as irrigation pipe and rebar integration strategies, realized as negative spaces through sustainable hybrid formwork mostly consists of recyclable 3DCP. A case-based empirical experiment of a full-scale green wall installed in a real-world interior project was conducted as validation of the method.

2. Method

2.1. PLANT MEDIA SPACE DISTRIBUTION AND PATH GENERATION

3DCP formwork relies on discrete stay-in-place molds as plant media spaces, and linking paths to connect such molds to the surface of the building block. Confined by the technique of continuous printing path generation, the previous research integrated the formwork of both functions, leaving only linear, thin, single-directional room for root development, and the green wall system has to be exposed on both sides of the wall (Wang et al., 2020).

Emerging concepts in discrete path generation (Retsin, 2016; Soler, 2017) allows us to consider 3DCP molds for different functions as separate entities. To introduce uneven distribution and multi-directional root development space, a series of vertically continuous clay volumes are placed inside the building blocks as plant media spaces. These volumes can vary in size, section profiles and distances to the surface of the building block, allowing for uneven distribution of plant media for root development and thus a wider range of selection for vegetation species.

To connect these clay volumes to the surface of the building blocks, a series of V-shaped linking paths are introduced to create openings on the surface of the building blocks for initial plant root development. As a measurement to maintain the structural performance around the surface of the building blocks, the minimum distance for the linking paths is set at 20mm per industry knowledge to allow for enough concrete material thickness. Since clay material needs to span this designated surface thickness with no support during formwork printing, drying, and casting, linking paths are designed to be redundant. Each plant media space is connected to at least two root development holes on the surface of the building blocks, while each hole is connected to at least two plant media spaces. This strategy also allows for one sided exposure of the plant media space. Figure 1(a) describes the organization of 3DCP strategy in plan.

Based on discrete path generation techniques, filling patterns of 3DCP formwork components can also be developed separately according to their functionality. For a green wall module cast with 3DCP molds, the formwork consists of plant media spaces, linking paths, and boundary molds. The external force conditions on all three parts are different. The lateral pressure on each plant media space is equalized in all directions, and the component itself sustains higher internal forces. The boundary molds sustain external pressure largely from directions perpendicular to the edge. The linking paths "float" in concrete in the initial cure phase. Previous research shows that such conditions can result in varied pathing strategies, respectively as boundary thickening (Guo, 2022), pattern filling (Jauk et al., 2023), and limited overhanging (Wang et al., 2020).

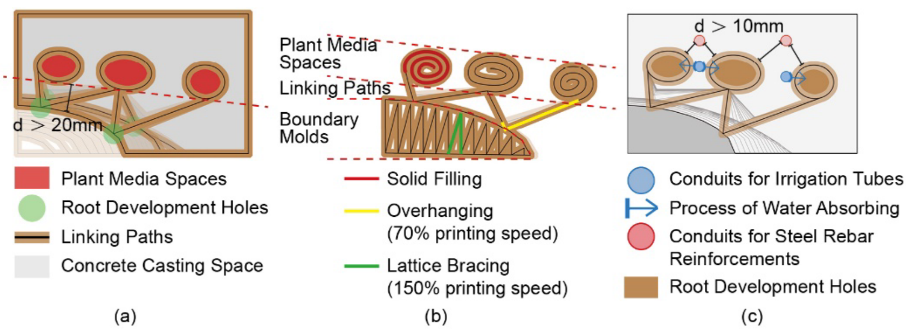

Figure 1. Organization of 3DCP Strategy. (a) The plan view of layers. (b) The automated generative path. (c) The placement strategies of the conduits.

Accordingly, we designate three pathing patterns for molds of different functions, namely solid filling, lattice bracing and overhanging. Solid filling aligns tool paths in parallel at the distance of the printing nozzle diameter, forming a solid body for plant media space to resist all directional pressure. Lattice bracing triangulates each layer with zig-zag courses pointed towards the direction of unidirectional force, creating boundary molds that are stronger in one direction with optimized printing time. Overhanging follows linking paths by gradually extending the cantilever from the printing plane to the top. To avoid time-consuming path optimization for each block, the paths are generated using discrete algorithms. The volumes are approximated by each path pattern individually, and the linking paths are generated through detected geometrical proximity. The automated generative path is described in Figure 1(b).

2.2. INTEGRATION OF CONDUITS THROUGH HYBRID FORMWORK

As lateral bracing and irrigation are two key components that need to be considered for modular green walls (Manso & Castro-Gomes, 2015), pre-installed conduits for both lateral support and water system can be an easy integration method in digital formwork fabrication (Meibodi et al., 2018). For green wall building blocks, modular conduits can be placed in relation to plant media spaces. As described in Figure 1(c), conduits for rebar reinforcements need to be placed at least 10mm away from plant media spaces to ensure structural performance, and permeable conduits for irrigation tubes are placed in direct contact with the stay-in-place molds to ensure water absorbance.

However, relying on 3DCP components for modular conduit placement can lead to uncontrollable cumulative error, because local deformation in 3DCP is difficult to avoid (Wi et al., 2020), and rebars placed accordingly become the anchor points of construction. To reduce error, we propose a hybrid reusable formwork method as described in Table 1, which seeks to align printing calibration with the calibration of anchor placement, effectively reducing cumulative error in a modular system.

Name	**Type**	**Material**	**Function**	**Optional**
Boundary Mold	recyclable	Clay	Defining geometry	No
Linking Path	stay-in-place	Clay	Linking plant media space to surface exposure holes	No
Plant Media Space	stay-in-place	Clay	Holding plant media	No
Base	reusable	Plywood	Printing base & error control	
Conduit	stay-in-place	PVC	Rebar conduits	No
Texture Frame	reusable	Rubber	Surface texture & frame	Yes
Adjustable Frame	reusable	Plywood	Lateral support	Yes

Table 1. Composition of Hybrid Formwork

The hybrid formwork is divided into four parts: 3DCP molds for customization, a reusable base for anchoring and error control, stay-in-place conduits, and optional frames for lateral bracing. The optional adjustable frames can be replaced with 3DCP framing, but are preferred in mass-customization since they reduce printing time with high reusability. Modular conduits are temporarily attached to the printing base through pre-drilled holes and a timber bar locator. The base also serves as the bottom of the formwork for casting. Figure 2 illustrates the installation and casting process.

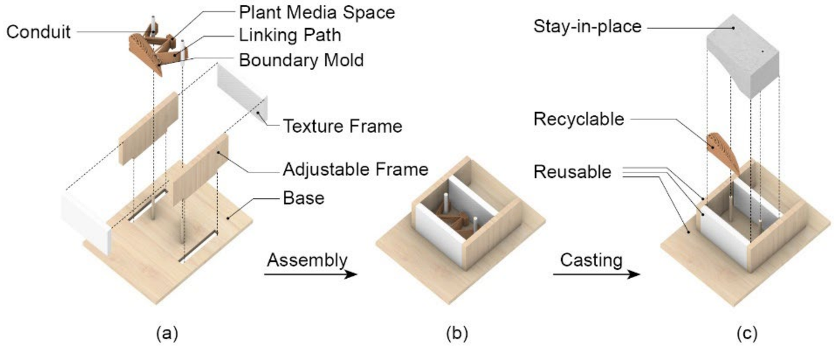

Figure 2. The hybrid formwork system. (a) The components of the hybrid formwork system. (b) The assembled hybrid formwork. (c) The description of reusability or recyclability for each component.

3. Fabrication Experiment

To validate our proposed framework, we conducted an empirical fabrication and construction test in an interior renovation project in the mountains in Anji, Zhejiang, China. Because the experiment is part of a real-world construction, specific site conditions and constraints from the overall scope of the project affected the deployment of our proposed methodologies, and the experiment process is described below.

3.1. GREEN WALL BUILDING BLOCK DESIGN

The test building blocks are designed as part of a feature wall facing the entrance of an exhibition space for local biodiversity and forestry protection. The overall geometry of the wall follows a gently curved surface, creating varied thicknesses across the wall and different plant media spaces. The wall is formed by a total of 90 unique, self-similar concrete blocks, with 29 green wall blocks and 71 regular ones which are fabricated with direct 3D concrete printing with the same conduit placement strategy. The wall design and the distribution of the green wall blocks are demonstrated in Figure 3(c).

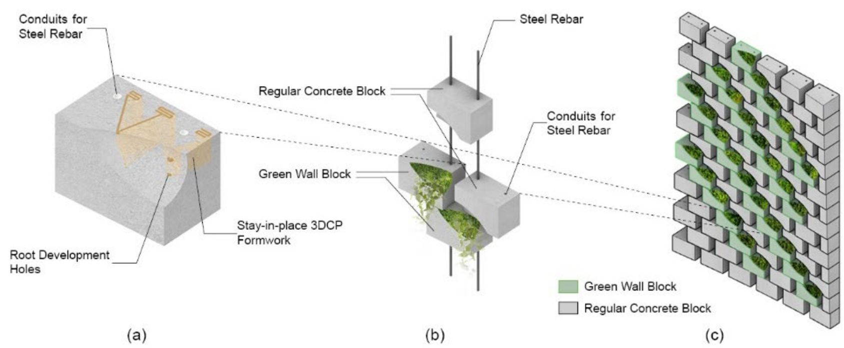

Figure 3. The green wall design. (a) The design of the green wall block (b) Connection between blocks (c) The distribution of the green wall blocks and regular concrete blocks

As shown in Figure 3 (a), each green wall block has an elliptical concave on its surface to better host the plants, on which exposure holes are located and connected to the inner 3DCP plant media space, allowing the plant roots to grow inward. The dimensions of the building blocks echo that of brick tiles on the existing floor, with a height of 150mm, a length of 220mm and a width ranging from 100mm to 192mm. The scope of the project does not involve change of the existing building's water supply system, and therefore only two conduits placed at 140mm interval are reserved in each building block for continuous vertical rebars connecting the floor slab and the beam above, as shown in Figure 3(b). Irrigation pipes were not installed in this experiment, and instead we used manual watering directly onto the leaves of the flora.

We choose a mixture of shade-loving moss, fern, and herbs such as Asiatic Jasmine all found locally in the mountainous area, since the wall faces north-east with limited natural direct sunlight. Both local fern and herbs are planted through cuttage, where then plants are cut on their stems and inserted into the plant media on the building blocks.

3.2. 3DCP SETUP

Considering the size of fabrication and quantity of clay material used in formwork, we use a Kuka KR10 R1100 industrial robot to perform the 3D printing task. For the end effector, a small custom-made screw pump propelled by a step motor is linked to a stainless-steel outlet of 6mm diameter as the printing nozzle for stable material delivery. The step motor of the screw pump is connected to a separate control box, which includes an independent power supply, a programmable step motor driver board and an I/O communication board connected to the control system of the industrial robot. This system ensures that the speed of the nozzle movement and the material delivery rate can be synchronized according to the need for different pathing strategies.

We use a pneumatic feeding system for the delivery of clay from a 1200mL material tank to the screw pump. An air compressor provides the tank's top allowable air pressure at 6psi to drive its piston. A translucent plastic tube of which the inner diameter is 10mm connects the tank and the inlet of the screw pump, allowing for visual monitoring of the quality of clay against potential air gaps. Commercial pottery clay product with a moisture level of around 45% was used based on knowledge from industry. The entire 3DCP system is shown in Figure 4.

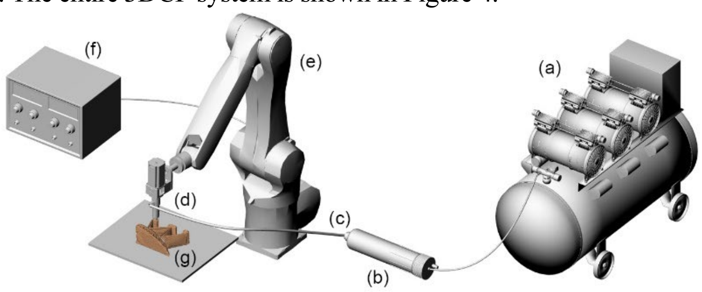

Figure 4. 3DCP Setup. (a) Air compressor (b)Material tank (c)Translucent plastic tube (d)Screw pump (e)Robotic arm (f)Control box (g)Printed clay formwork

3.3. FABRICATION

During the initial printing test, the paths of the three different patterns were prone to two failure patterns: the linking path connects to the boundary molds with a 20mm overhang and a small contact area, and thus was prone to fracture. In addition, the lattice bracing section shrank in area from bottom to top with the same number of zig-zag turns, resulting in material buildup. The discrete path generation strategy allowed us to assign optimized printing speed settings to different parts. For overhangs, we reduced the nozzle movement speed by 30% while maintaining the extrusion speed at 20mL/min. In lattice bracing, we increased the nozzle movement speed by 50% (Figure 1b). All formworks of 29 blocks were successfully printed continuously and uniformly. Each 3DCP formwork with a height of 150 mm took less than 30 minutes to print, and all formworks took a total of 14.5 hours to print, spreading over 6 days.

The printed 3DCP formwork was cured for 24 hours to reach the strength suitable for concrete casting. To facilitate the fixation of the 3DCP formwork to the frame formwork, the bricks are cast with the top surfaces facing down. A total of 5 sets of reusable components were produced and reused for 6 times each, including one failed casting attempt due to concrete mixture error. After assembly, a thin layer of Vaseline was applied to the surface of non-clay components as the demolding agent. A customized self-compacting cement with short glass fiber was used for casting, and the same mixture was used for 3D concrete printing of the non-green wall blocks. When cured, the concrete mixture has a compression strength equivalent to that of C25. The 24-hour curing time of the clay formwork coincided with that of the concrete, allowing for smooth rotation between demolding - printing and assembly - casting procedures.

During demolding, the plywood and rubber frame could be easily removed and reused, and the PVC tubes were left in the blocks as a reserve for tensile lateral bracing. The boundary molds portion of the 3DCP was mixed with water and recycled. This way, all parts of the hybrid formwork were either reused or recycled, ensuring material sustainability during the fabrication. The fabrication process is shown in Figure 5.

Figure 5. Procedures of fabrication. (a) Printing clay formwork. (b) Assembly. (c) Casting. (d) Demolding with water. (e) Fabricated green wall block. (f) Top view of block showing the plant media space and conduits. (g) Block with plants. (h) Plants grow into the block.

3.4. ON-SITE ASSEMBLY

Rebars with spacing of 140mm were pre-fixed into the slab and the top ends were left free to allow bricks to be inserted from the top through the reserved conduits. The bricks were pre-sorted using a numbering system after delivery to the site and installed from bottom to top, as shown in Figure 6(a). Structural adhesive was applied to the gaps between the conduits and the rebars to prevent rusting. The same adhesive was also applied to the contacting surfaces between the bricks to replace mortar. The entire wall was installed by local workers within 2 days. To give the plants a better substrate for the initial phase of the cuttage, we substituted the topmost layer of brittle clay (less than 10mm deep) that dried up during the construction process with local soil. The rebars then were connected to the beam above.

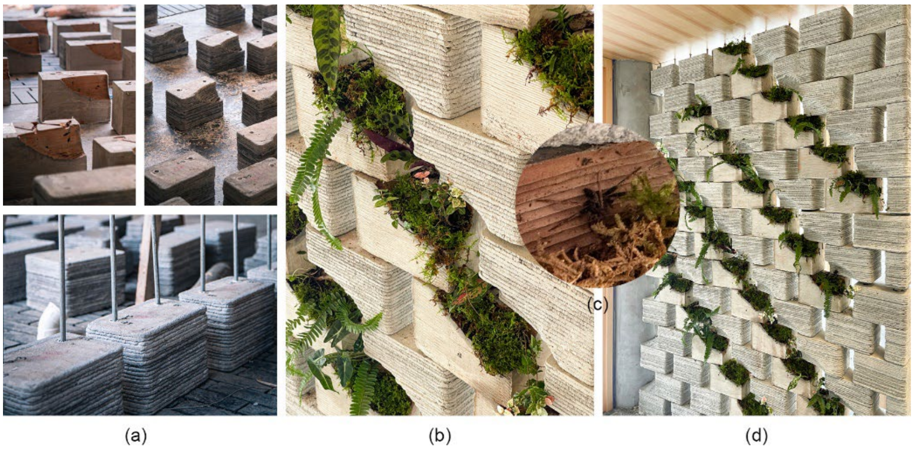

Figure 6. The green wall. (a) On-site assembly. (b) Plant status after 90 days. (c) Local ecosystem after 90 days (d) Final construction.

3.5. TEST RESULTS

The green wall building blocks from the construction test turned out geometrically faithful to the original design with controllable tolerance, which resulted in smooth assembly and visual harmony with the 3D concrete printing blocks. The error of construction majorly appeared in acceptable height differences from adjacent building blocks, largely due to the manual casting process when the amount of concrete used in each pour was not quantitatively controlled. The differentiation in 3DCP formwork functions and discrete path pattern generation, which allowed for swift adjustment of printing speed and adaptability to non-standard, unique serial component forms, exhibited adaptability during the mass-customization process.

After the installation, we applied twice per week regular watering and observed the performance of the wall through an observation period of 90 days. As Figure 6(b) demonstrates, most plants have survived the observation period, including the herb cuttage. We have also discovered insect and spider nests under the vegetation, indicating the formation of local micro-ecosystems, as shown in Figure 6(c).

4. Reflection and Discussion

This research develops a methodological framework to integrate uneven distribution of plant media spaces, lateral bracing, and irrigation systems into multifunctional green wall blocks through sustainable hybrid formwork featuring recyclable 3DCP and reusable panel materials. Aiming at mass-customization, the research further proposes discrete path generation and precision alignment through reusable formwork for adaptability and quality control during the fabrication process. The feasibility test in a real-world interior project shows that the wall can be vertically self-supporting, and such building blocks can be potentially used as exterior infill walls if insulated from the interior. Meanwhile, the 3DCP component design-fabrication framework can be extended to the fabrication of other building components.

However, as an early-stage research, future work needs to be done to validate some of the assumptions of the proposed system. The objective of 3DCP formwork for green wall blocks is to reduce the structural dependence of conventional green wall units to reduce material cost and thus carbon footprint. However, the current method does result in smaller root development space and limited planting area. Thus, a comparative study needs to be done between different systems' initial and long-term sustainability impacts.

Secondly, the right material for 3DCP stay-in-place formwork for the use of green wall blocks is still to be studied. Commercially available clay is not the best soil substrate for green wall plants. However, the material's operability for 3DCP especially for overhanging over a short distance played a substantial role in our strategy. We envision that a better material solution be a mixture of clay and soil which balances its performance in printing and as a plant media.

In addition, further research needs to be done to better understand the relationship between filling patterns, formwork functions and deformation. In most existing works, filling pattern studies have been largely associated with deformation control in direct printing of building components, and the filling patterns applied to formwork in our experiment were based on our best knowledge instead of empirical data. Because filling patterns can help significantly optimize printing time and material efficiency, and are strongly linked to discrete generative pathing strategies, further understanding of their impacts on formworks needs to be studied.

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