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Lamella-inspired 3D Concrete Printed Column-slab System: Balancing Act for Productivity and Sustainability

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ABSTRACT

3D concrete printing (3DCP) is a promising technology for building diverse cities as it can realize customized elements with an automated construction process. However, in large-scale construction, 3DCP is still facing challenges in balancing productivity and sustainability. First, the geometries that can be printed fast demand increased concrete usage to ensure stability during the printing processes. Second, geometries with material-saving potential usually involve intricate segmentation and assembly processes to ensure printable shapes. To address such conflicts, this paper develops a novel form-finding method inspired by mushroom lamellae and then proposes a column-slab system based on this method. The lamella-inspired method aims to 3DCP the geometries in their final orientation by adding support through folds introduced in the unprintable parts. From a productivity perspective, this method folds the surface of the column-slab system according to their overhang and cantilever degrees, transforming the structure into a self-supporting geometry suitable for 3DCP. From a sustainability perspective, the lamella branching pattern aligns with material-efficient structural frameworks, eliminating the unnecessary concrete inside the system. Subsequently, a 3DCP prototype and a Fused Deposition Modeling (FDM) scaled model are presented to demonstrate the feasibility of the proposed method. In conclusion, the paper outlines a comprehensive design-to-construction workflow for a 3DCP column-slab building system suitable for denser urban areas. This method considers not only material reduction of the result but also labor savings during the handling of the printed components.

1. Introduction
1.1 Background

3D Concrete Printing (3DCP) emerges as a promising technology for shaping diverse architectures by enabling customizable designs through an automated construction approach. Unlike traditional

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casting methods, 3DCP adopts automation to precisely deposit and stack fast-setting concrete. Such a layered extrusion process eliminates the need for bespoke formwork in concrete construction. This innovation not only enhances construction efficiency for a wider range of design scenarios but also mitigates hazardous labor conditions relating to the fabrication of complex structures. Moreover, as a disruptive technology, 3DCP facilitates the construction of more sustainable design options, such as structure-optimized shapes and hollow core geometries. Given the significant carbon emissions associated with concrete [1, 2], leveraging 3DCP to achieve lean construction is important in contemporary construction practices.

However, upscaling 3DCP oscillates between sustainability and productivity. Essentially, this contradiction arises from the prevalent practices of employing 3DCP primarily for compression-dominant walls rather than compression-tension structural elements. In such projects, walls, structurally similar to masonry, are typically 3D printed, while load-bearing elements like columns, beams, and slabs are often cast on-site or prefabricated [3, 4]. This preference stems from multiple considerations including the cost, 3DCP regulation, rebar integration, geometry printability, etc. For example, printing horizontal structural elements involves technical challenges, as the void tunnel for longitudinal reinforcement requires the structure to be printed vertically (i.e., rotate the digital model 90° and then print in the Z direction) while such a printing approach necessitates substantial printer height. Currently, segmentation is a dominant solution in academia [5, 6], with the first multi-story buildings being constructed [7]. Nevertheless, given the complex context and the multitude of factors involved, the industry tends to favor the 3DCP of small-scale wall enclosures, which is the most direct implementation of 3DCP in construction under existing regulations.

The reliance on productivity tends to homogenize construction workflow as well as design methods, limited to one or two floors and predominantly comprising single-family houses. Consequently, the scale of 3DCP projects keeps increasing in its footprint rather than the height [8]. Without an approachable printing method to shift this trend, such a horizontal development pattern might catalyze the proliferation of identical, carbon-intensive buildings, impairing the diversity and sustainability of denser constructions.

Confronting the challenges of homogeneity and material waste, the 3DCP industry needs sustainable and productive methods to liberate the current construction workflow from the masonry-dominant approach. In response, this research proposes a novel 3DCP building system that only utilizes concrete in structural frameworks and still aligns with the demands of on-site construction. Ideally, the proposed method would streamline future concrete printing projects, where concrete walls are solely employed for structural needs, while sustainable alternatives are utilized for the rest of the enclosure components.

1.2 State of the Arts

The integration of ribbed slab with mushroom column presents a promising solution for streamlining the 3D printing process of structural framework. Pioneered by visionaries like François Hennebique, Pier Luigi Nervi, and Angelo Mangiarotti, this column-slab system revolutionizes the design of reinforced concrete structures by improving the force transmission and removing unnecessary material inside the structure. From a sustainability standpoint, the ribbed slab system can reduce concrete usage by 30-40% compared to the equivalent flat slab [9], with the empowerment of 3DCP, digital cutting, and binder-jetting, the reduction can achieve approximately 50% [10]. Furthermore, the inclusion of mushroom columns mitigates punch-through force between columns and slabs, thereby reducing the need for reinforcement in vertical-to-horizontal intersection areas. From a productivity standpoint, even though the historical underutilization of such structures results from significant formwork costs, advancements in digital fabrication technology now offer a viable pathway to efficiently realize these designs.

The following research projects (Fig. 1 and Fig. 2) underscore the potential of using 3DCP technology to construct the mushroom column and ribbed slab while also highlighting challenges in construction efficiencies.

Firstly, the large overhang shape on the mushroom column exhibits printability issues, as the maximum overhang of the column capital usually exceeds 45° while most 3D printed concrete has an overhang limit below the value. Consequently, fabricating these capitals often necessitates additional design-to-fabrication strategies. One approach involves segmenting the capital into multiple pieces (Fig. 1a), each rotated to a proper printing direction. The process ensures that every part of the shape remains within the overhang threshold during printing [11]. However, this method inevitably encounters the interface issue and demands additional efforts for scaffolding and assembly. Alternatively, printing the mushroom column upside down (Fig. 1b) can improve the self-supporting abilities of overhang geometries, as the tension-dominant overhang structure can temporarily become a compression-dominant structure while printing [12]. Yet, this technique required difficult handling of fragile, unreinforced components produced only in factory settings. Another related strategy entails printing the ultra-thin formwork of the column capital using thermoplastics (Fig. 1c) [13]. While this approach maximizes material efficiency and solves the reinforcement issue, the fabrication time of such a high-resolution formwork makes the strategy unscalable.

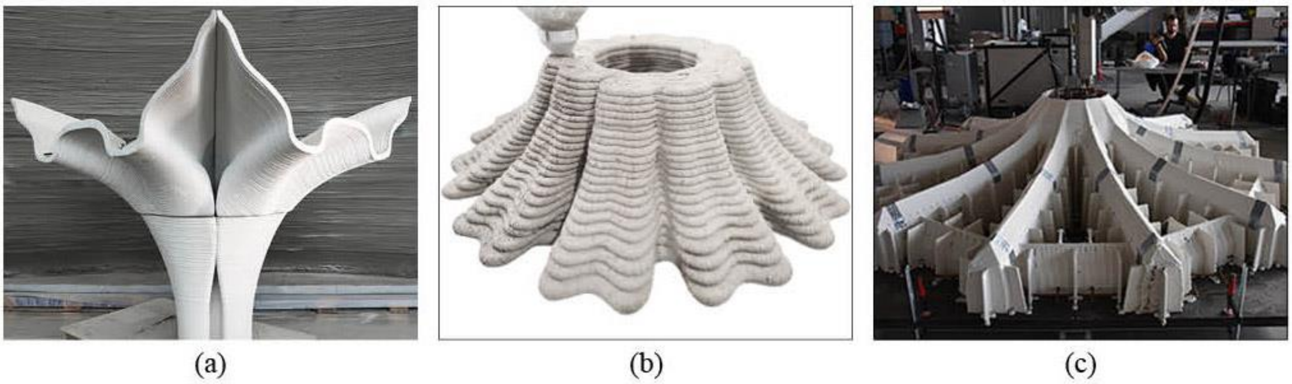

Fig. 1. Research projects about 3DCP mushroom column capitals (a) Column-slab interfaces from ETH DBT [11] (b) Mushroom column prototypes from Tsinghua University [12] (c) 3D printed ribbed formwork from ETH GKR [13]

Secondly, the ribbed slab features numerous non-standard cantilever soffits, making the slab impractical for bottom-up printing. To address this, a hybrid approach combines 3D printing with Computer Numerical Control (CNC) to fabricate slab formwork [14] (Fig. 2a). In this technique, researchers print only the formwork's side panels and use CNC machining to cut horizontal panels from plywood. However, manual assembly and demolding processes are still required. Alternatively, researchers can invert the digital model and print concrete directly as stay-in-place formwork from an opposite direction, enabling direct printing of the cantilevering soffits on the print bed [9] (Fig. 2b). Nevertheless, this approach divides the concrete formwork into multiple units, these units should be inverted back after solidifying and precisely repositioned to build the formwork, thus the complexity of fabricating such slabs increases. Another approach is printing concrete as the structural component, like the compression-only slab [15] (Fig. 2c). This method eliminates the formwork assembly process, allowing the slab to be printed in one go. Despite the advancement, the construction of such structures demands a preprinted substrate [16], potentially increasing material usage as construction scales.

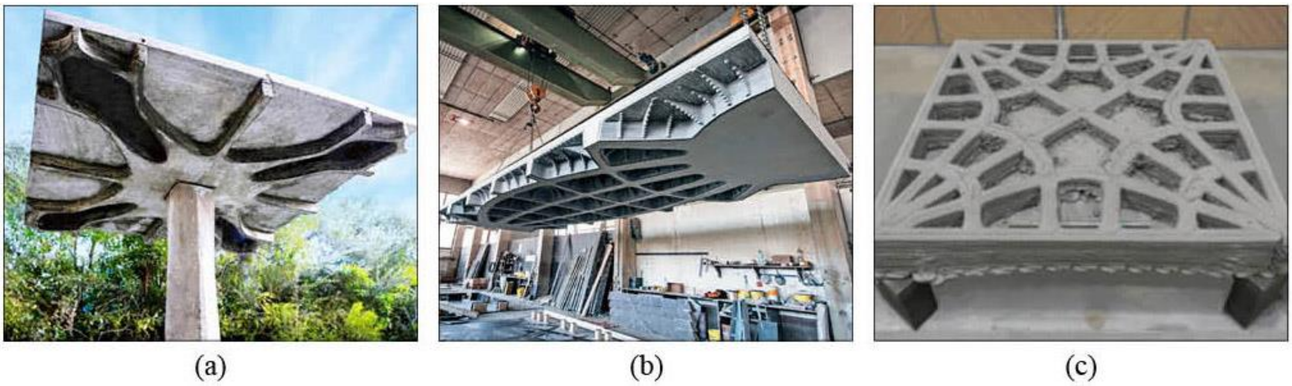

Fig. 2. Research projects about 3DCP ribbed slabs (a) PrintNervi project from RMIT University [14] (b) Light weight concrete ceiling from Graz University of Technology [9] (c) "Extrusion to Masoning" project from Tongji University [15]

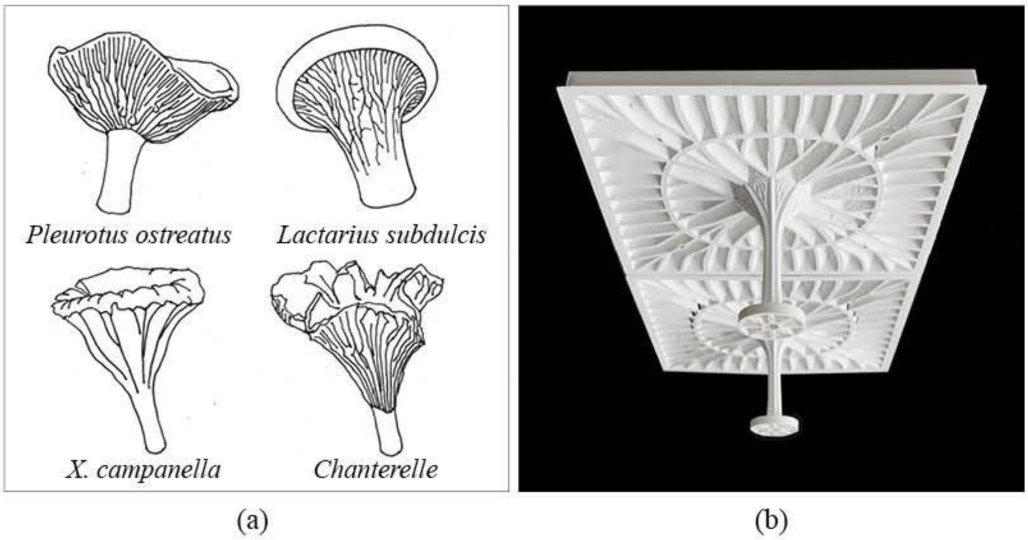

Fig. 3. (a) The mushroom lamellae (b) The research result: lamella-inspired column-slab system

1.3 Lamella-Inspired 3DCP Column-slab System

This research is inspired by mushroom lamellae (Fig. 3a), which are formed through the differentiation of dikaryotic hyphae during mushroom growth [17]. Even though the lamellae are naturally generated for spore production and dispersal, the morphology of their ribbed structure and branching pattern show potentialities in shaping column-slab systems. Our initial print tests have demonstrated that the lamella structure enhances the overhang capacity of 3DCP structures, enabling self-supporting printing of structures exceeding 50° overhang (Fig. 4). Therefore, the lamella structure can be applied on the mushroom column capitals with large overhang parts, allowing the capital to be printed in its final orientation. Additionally, the lamella pattern presents a novel approach to subdividing a cantilever surface. Intuitively, this subdivision pattern can separate the slab soffit into several evenly distributed units, each unit is just narrow enough to form a printable pyramid shape under the slab (Fig. 3b). Moreover, this pattern can follow the principal stress lines of the slab, ensuring its structural performance and enough space for reinforcement insertion. Hence, by incorporating lamella structures into the proposed column-slab system, it becomes possible to eliminate all the unprintable shapes within the ribbed slab and mushroom column while achieving significant material savings.

(a) (b)

Fig. 4. (a) Initial printing test for shell structure with maximum 50° overhang (b) Initial printing test for rib structure with maximum 50° overhang

1.4 Significance, Gaps and Objectives

The significance of this research lies in its quest to strike a balance between sustainability and productivity in large-scale 3DCP column-slab systems. It introduces bio-inspired methods to address the printability issues for the column-slab system, making it possible to print only the structural framework instead of the enclosure system. As a result, the overall concrete consumption for 3DCP buildings can be reduced without the involvement of additional labor forces. The research idea is proved by the 3DCP of a prototype and FDM printing of a 1:30 scaled column-slab system model. However, the research has yet to undergo verification through 1:1 fabrication and structural testing, which will be conducted in future research.

The goal of our research is to develop design-to-print strategies for mushroom columns and ribbed slabs, enabling print-structure-only capabilities of large-scale 3DCP projects in future urban constructions. The specific objective of this paper is to ensure the self-supporting printing processes of these structures by applying the lamella algorithm. Therefore, this paper will begin by introducing a method for generating lamella structures, followed by two distinct design workflows for designing and printing mushroom columns and ribbed slabs (Section 2). Next, a series of printing tests will be conducted to validate the printability of the proposed designs, with subsequent outlook given to the real-world construction process of the lamella-inspired column-slab system (Section 3). Finally, the contributions and key findings of this research will be summarized in Section 4.

2. Methodology

2.1 Lamella Generation Methods

The lamella generation method is the evolution of a radial fractal that is commonly used to imitate the lily pad structure [18, 19]. The exponential branching rule of the original algorithm is replaced by the closest point indexing process, which is guided by a series of control curves as well as division lengths (Fig. 5). Firstly, the control curves are generated within a given boundary, marking the branching position for each iteration. Secondly, an ideal division length is applied on each control curve to divide it into control points. Then, the generation of the branch starts from the center of the shape, connecting the outer control points with the nearest inner control point. Finally, a branching system of lamellae can be generated when the iteration reaches the outer boundary. Based on this generation logic, an evenly distributed lamella pattern can be achieved by adopting a constant division length, which can be applied in subdividing the ribbed slab. The division length can also be correlated with the overhang angle of the mushroom column, allowing more lamellae to support the large overhang part and less to the regular part.

In three dimensions, the stability of the lamella structure can be verified by measuring the overhang angle before and after folding a surface (Fig. 6). Folding the inclined or cantilever surfaces enables a reduction in local overhang while preserving the original overhang angle at the ridge of the shape. Importantly, this folding process does not introduce holes or new unprintable parts to the structure, which matches the continuous path requirement for 3DCP.

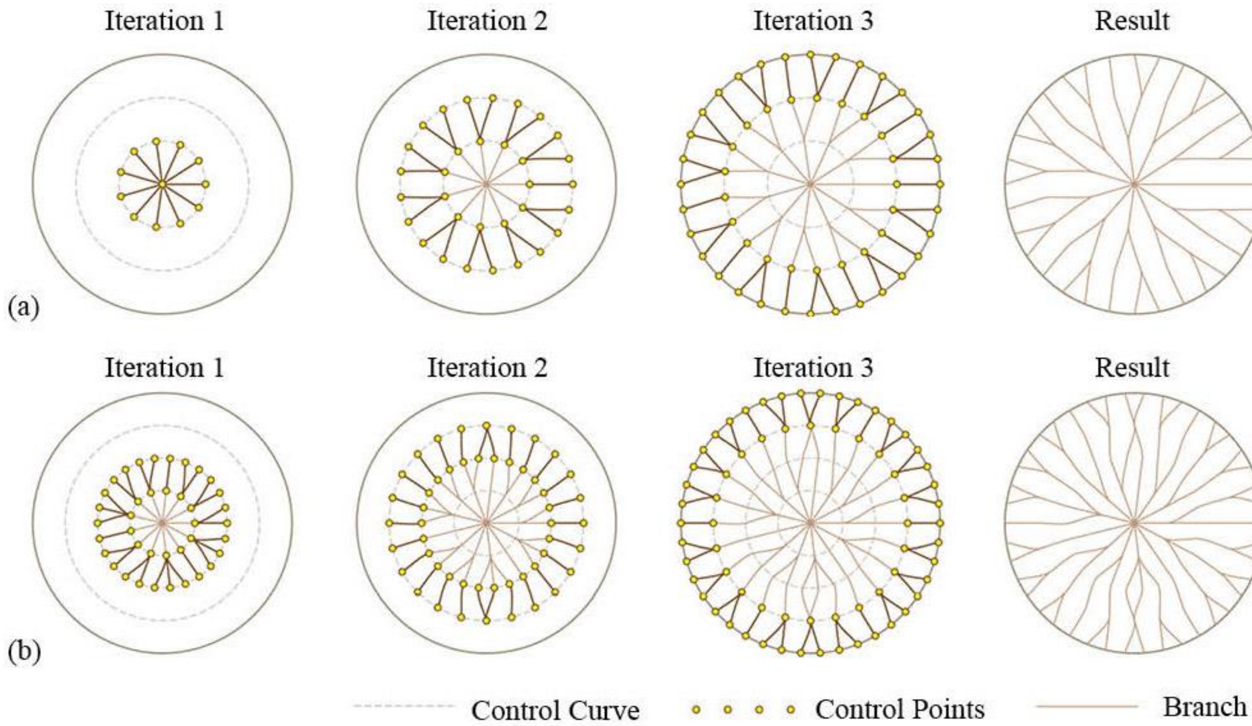

Fig. 5. Lamella branching process (a) Lamella branching process with constant division length (b) Lamella branching process with varying division length

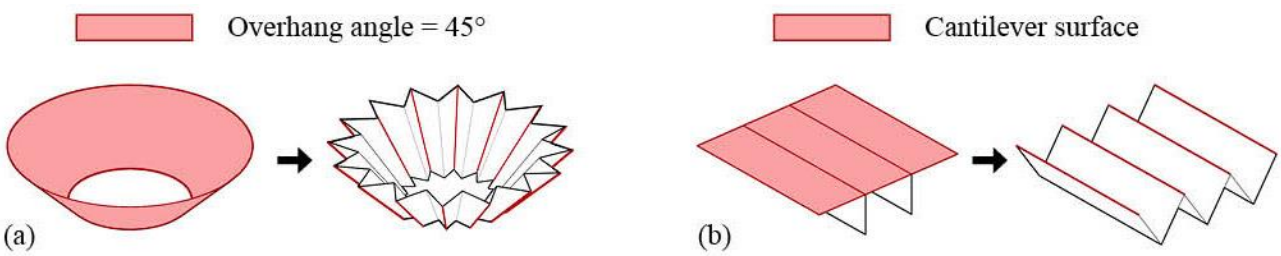

Fig. 6. Lamella folding process (a) Folding an inclined surface (b) Folding a cantilever surface

The following methods will demonstrate how the branching and folding mechanism of lamellae can be effectively applied in the column-slab system. In this study, the design of the column-slab system draws inspiration from the Nervi structure system [20], which incorporates both mushroom columns and ribbed slabs. Concretely, the slab spans 8m with a height of 3.5m, and the concrete filament dimension is 30mm width × 10mm height.

2.2 Lamella-Inspired Ribbed Slab

The lamella branching pattern on the ribbed slab is designed with two considerations. Firstly, it ensures that each subdivided unit on the slab can be folded and printed in a horizontal position. Secondly, it aligns with the principal stress lines. The force transmission mechanism of the given surface is analyzed using Karamba 3D, a plugin based on Grasshopper [21]. Specifically, an initial simulation is carried out to identify the stress distributions on the slab surface without rib support. Then, the principal stress lines are generated on the surface by following the directions in which the bending moments reach their extreme values (Fig. 7a). These identify the directions where material failure is most likely to occur and thus where rib supports are necessary. Subsequently, reference curves are extracted from the principal lines (Fig. 7b), serving as the rib system to support the slab as well as the control curve to branch the lamella (Fig. 7c). As elaborated in Eq.1 and Eq.2, the distances between control curves and control points are correlated with the structure span and rib sizes to ensure that each subdivided unit is narrow enough to be folded into pyramid shapes.

$$L = W_{r2} + 2D_r \cdot \tan(\theta) \tag{1}$$

$$N_C = 2 \times int[\frac{S - 2R_p}{4} - \frac{W_{r1} - W_{r2}}{2L}] \tag{2}$$

where L represents the division length and N_C represents the number of control curves, W_{r1} is the width of the main rib while W_{r2} is the width of the secondary rib, D_r is the depth of the rib, θ signifies the maximum overhang angle of the concrete ($\theta = 40°$), S represents the span of the column-slab system, R_p is the radius of the mushroom column's control perimeter.

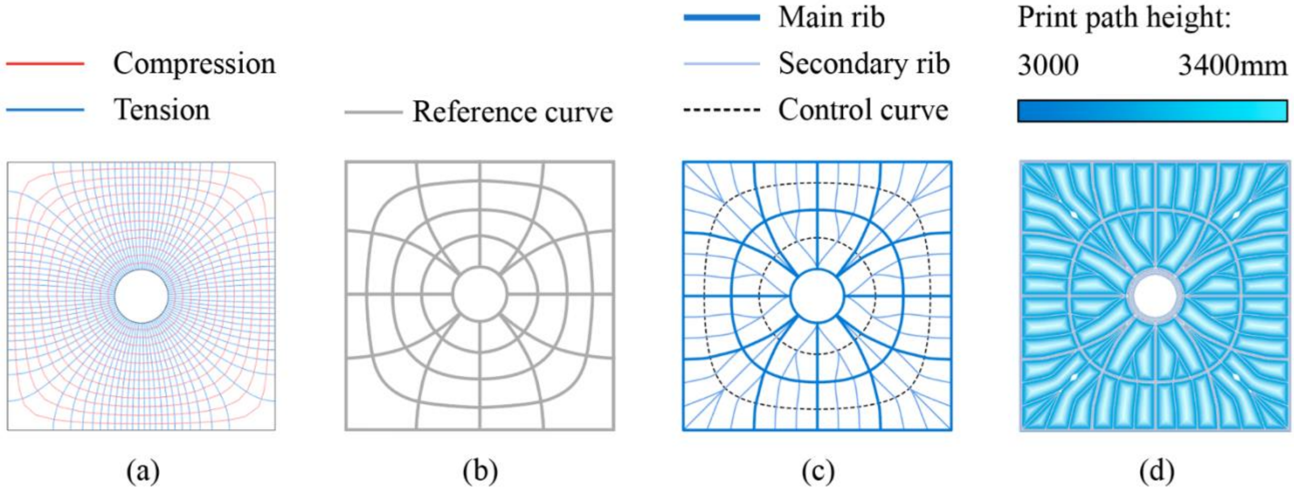

Fig. 7. The generation of the lamella-inspired ribbed slab (a) Principal stress lines on the slab (b) The extracted reference curves (c) The rib system to support the slab and the lamella pattern to subdivide the surface (c) Print paths to construct the soffit

A novel print path generation method is then applied on the surface to convert the lamella pattern into a folded soffit (Fig. 7c). The challenge to fold the surface lies in the irregularity of each subdivided unit. Since these units are unique and irregular, it is difficult to directly calculate the height and shape of their ridges by the given boundary and target inclination angle (the value θ in Eq.1). Moreover, concave units might also have multiple peaks, which make the folding mechanism unpredictable. To address this, this study employs a loop function to iteratively offset the units' boundaries instead of actually folding these units. The offset distance (D_o) of each iteration is correlated with the target inclination angle and print height (Eq. 3). In each iteration, a double offset scheme is adopted to remove sharp corners and the bottleneck effect [22]. The resulting paths are then moved upward according to their corresponding print heights, forming the print path to construct a continuous slab soffit.

$$D_o = h \cdot \cot(\theta) \tag{3}$$

where D_o is the offset distance to generate the print path, h is the print height (10mm), and θ represents the target inclination angle, which is also the maximum overhang angle of the concrete (40°).

2.3 Lamella-Inspired Mushroom Column

The large overhang angle of the column capital is the major problem to solve in the design of the mushroom column. To address this, a two-layer print path generation workflow is proposed (Figure 8). The design includes an inner surface with a maximum overhang angle of about 70° and an outer surface with distributed lamellae to support the inner surface. The lamella generation of the outer surface involves two steps (Fig. 8a). First, the surface is creased to form eight main lamella branches, leaving space for vertical reinforcement. Second, tiny and dense lamellae are generated to crease the outer surface inward and attach to the inner surface, providing sufficient support to stabilize the overhanging shape.

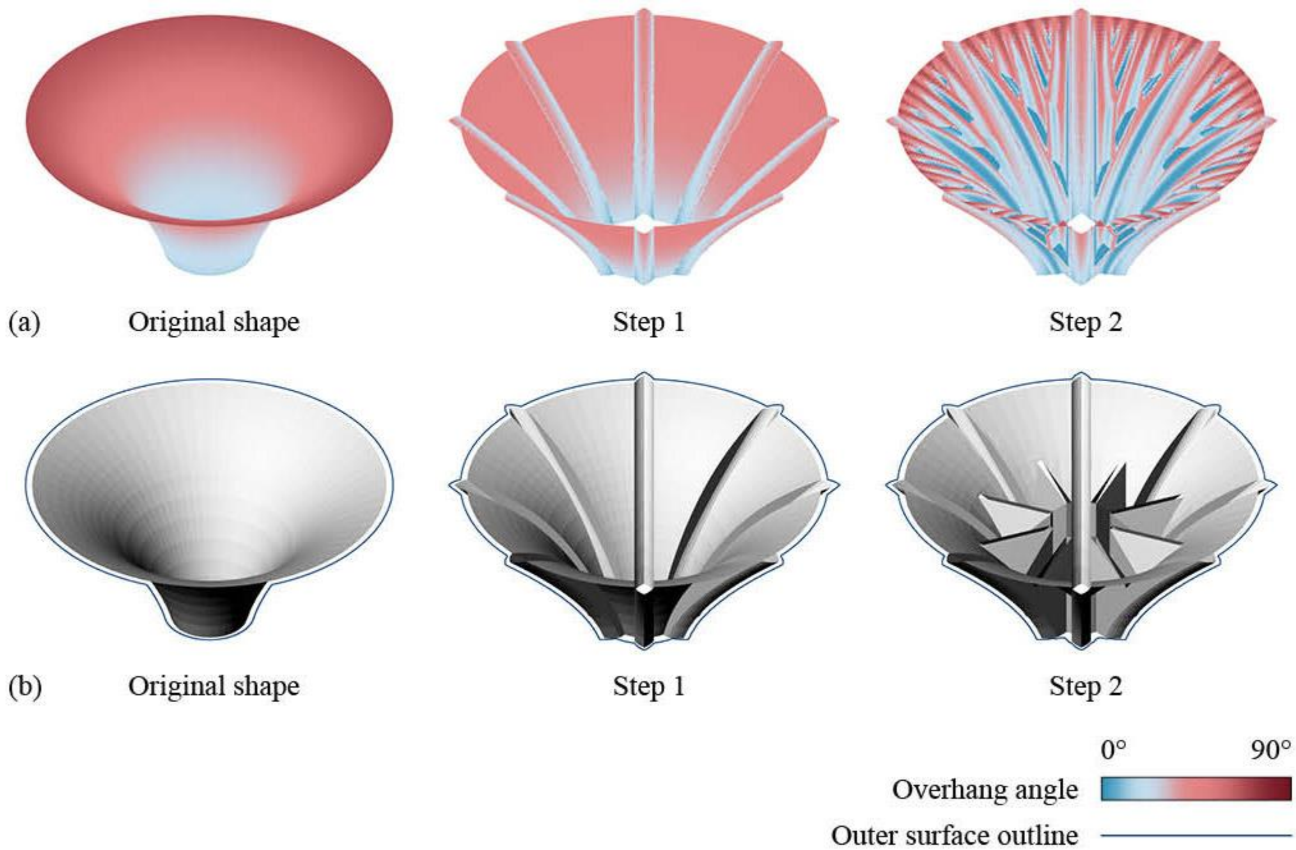

Fig. 8. The generation of lamella-inspired mushroom column (a) The folding process of the outer surface (b) The folding process of the inner surface

In designing the inner surface, a key strategy involves generating the supporting structure inside the column while ensuring enough space for reinforcement. Theoretically, the inner support may seem unnecessary as the folded outer surface can also serve as a stay-in-place formwork. However, the inner support serves to delineate areas that do not require casting or reinforcement, thereby further reducing the consumption of concrete. Additionally, it helps to stabilize the entire column during printing and transportation, as well as enhance its strength to withstand hydrostatic pressure during casting. The generation of the inner support can be considered as another folding process conducted on the inner surface (Fig. 8b). Ultimately, the original geometry becomes a delicate mushroom column, with a folded outer surface that is printable while the inner surface retains a significant overhang for functional use. Both the outer and inner surfaces are then sliced to generate the print path.

3. Results

Two prototypes are printed to demonstrate the feasibility of the proposed method. Firstly, an 800×800×750mm prototype is printed with concrete to verify the printability of the lamella-enhanced structure. Secondly, a 1:30 FDM printing test is presented to mimic the actual printing process of the lamella-inspired column-slab system.

3.1 3DCP Prototype

The prototype design integrates the lamella generation methodology for both column and slab components. On the one hand, it features a flat upper surface with evenly distributed lamellae, corresponding to the subdivision challenge of the slab. On the other hand, it includes a lower surface with lamellae on the overhanging part, tackling the overhang issue of the column capital. Due to the limited dimensions of this prototype, space for reinforcement is not incorporated in this design. The printing is executed by a KUKA KR210 R2700 robot, with a continuous printing process of approximately 2 hours (Fig. 9). The printing results demonstrate high quality in overhanging shapes as well as the flat upper surface, proving that the implementation of the lamella algorithm not only enhances the structural stability during printing but also introduces organic details to the prototype.

Fig. 9. 3D concrete printing process of the prototype

3.2 FDM Printing Column-Slab System

As the real-scale project is ongoing, a 1:30 FDM printed model is presented to demonstrate the printability of the system (Fig. 10). The FDM printing test was conducted using a Raise 3D desktop printer with Polylactic Acid (PLA). The size of PLA filament is 1mm width × 0.33mm height, maintaining the same proportion as the actual 3DCP. Both the mushroom column and ribbed slab in this system can be printed in the Z direction without segmentation or reorientation.

The continuous printing of the mushroom column shows the effectiveness of the lamella algorithm in improving the self-supporting ability of overhanging geometries. As illustrated in Fig. 10, the algorithm facilitates the continual formation of tiny folds on the outer surface. These folds provide essential support for the inner surface featuring large overhangs. Such an overhanging shape allows the column capital's core to achieve a smooth vertical-to-horizontal transition, which is essential for the subsequent reinforcement to mitigate punch shear. Notably, two features of the mushroom column can be observed through the FMD printing: the hollow core designed for reinforcement and the voids generated in between the inner and outer surface to reduce material usage.

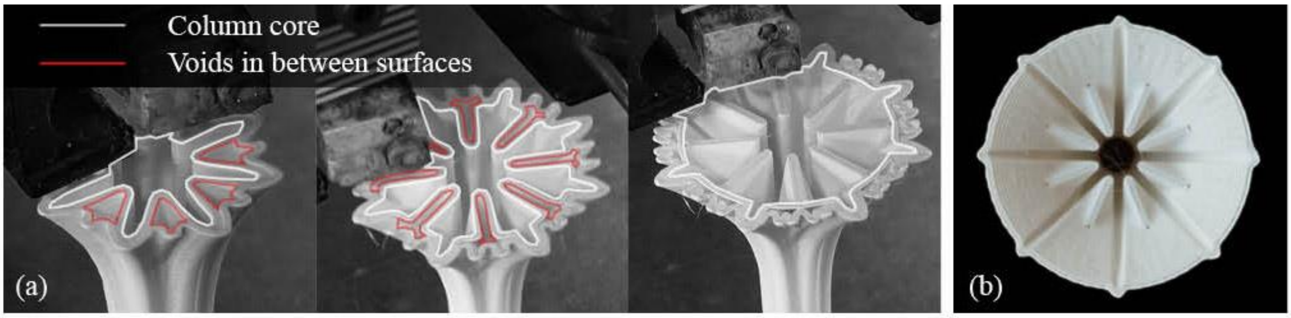

Fig. 10. FDM printing mushroom column (a) Printing process (b) Top view

Fig. 11. FDM printing ribbed slab (a) Printing process (b) Bottom view of the soffit (c) Bottom perspective of the lamella column-slab system

The formation of pyramid shapes eliminates all the cantilevering parts of the ribbed slab, it also allows the slab formwork to be constructed by sequential printing method. Specifically, the typical contour crafting method prints every part of the current layer before proceeding to the next. On the contrary, in sequential printing, the printhead initiates each new printing sequence from the base of the pyramid after completing the previous one, thereby reducing associated artifacts caused by frequent extrusion halts. The contour crafting method remains necessary in FDM tests to avoid the collision between the bulky extruder and the pyramids (Fig. 11). While, in actual 3DCP of lamella slabs, sequential printing becomes approachable as most concrete printers feature a tapering printhead. Additionally, unlike the vertical formwork used in traditional ribbed slabs, pyramids on the lamella slab feature tilted surfaces that prevent collision with the tapering print head.

3.3 Outlooks

In real-world construction, mushroom columns can be printed in situ, while ribbed slabs can be printed nearby and then assembled onto the columns after both structures are reinforced (Fig. 12). The 3D-printed elements of the column-slab system function as stay-in-place formwork. Once the printed concrete is set, reinforcement cages can be inserted into these structure components. Before casting the reinforcement area, starter bars should be embedded at the connection positions (i.e., the top of the column and the center of the slab) (Fig. 12c). The column core and the reinforced rib should be cast with concrete, while other empty spaces inside these structures can remain hollow or be filled with lightweight material. Lifting points and reinforcement mesh are also embedded within the slab before assembly. Subsequently, the slab can be hoisted and installed atop the in-situ columns, where all starter bars are interconnected. Finally, the connection area and the slab top are cast together to ensure structural integrity.

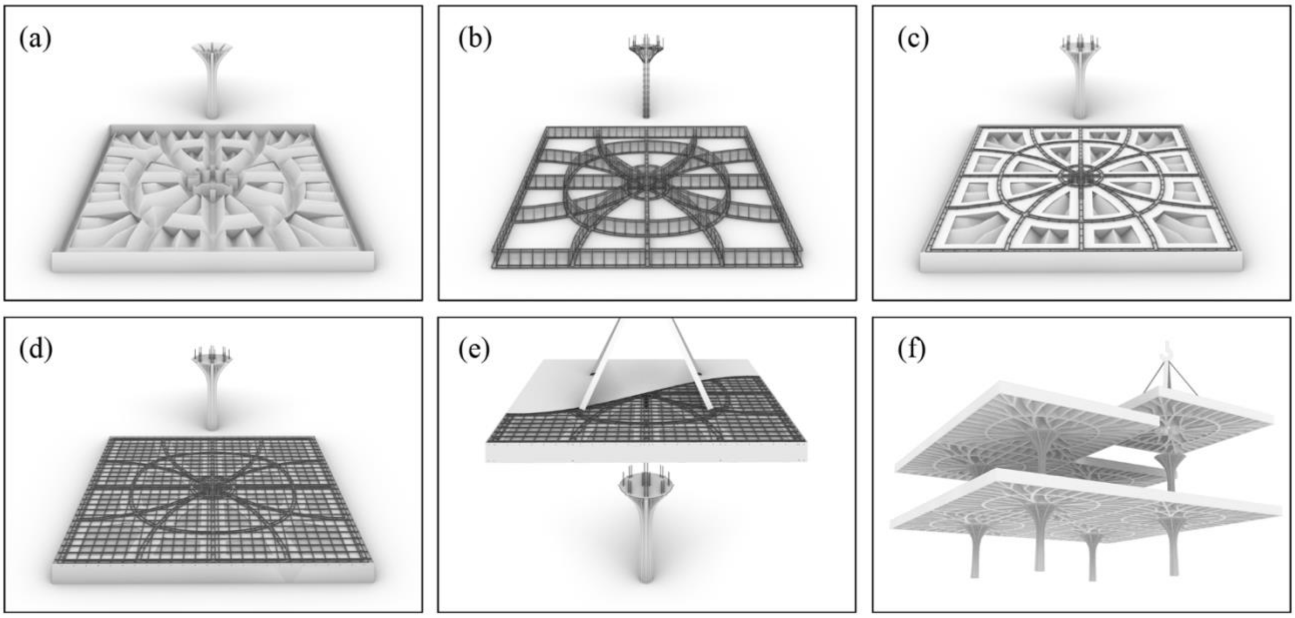

Fig. 12. The fabrication processes of lamella-inspired column slab system (a) 3DCP stay-in-place formwork (b) Reinforcement cages (c) Inserting reinforcement cages in the formwork and casting the main ribs (d) Installing reinforcement mesh on the slab (e) Lifting, assembling, and casting the slab (f) An outlook for future constructions

The lamella column-slab system provides an example of printing a material-efficient structure through a fast construction process. From a sustainability standpoint, the lamella system provides an option to print only the structural framework, which allows for the substitution of more sustainable materials for concrete in facade applications. From a productivity perspective, the lamella system eliminates the need for manual assembly of formwork. It is comparable to 3DCP enclosure systems in terms of construction efficiency, because both systems feature continuous printing processes as well as simple installation steps. This aspect makes the printing of column-slab systems a feasible task in real-world scenarios. Furthermore, the lamella-inspired printing process is not reliant on advanced printing techniques like non-planar printing. Hence, it is adaptable to both robotic and gantry systems, facilitating its application in both in-situ printing and prefabrication settings. By offering a practical and novel design-to-construction workflow, the lamella-inspired method is possible to enhance the constructability of large-scale, multi-story 3DCP projects in the future (Fig. 12f).

4. Conclusion

The presented work shows that the lamella-inspired 3DCP column-slab system can achieve a balance between sustainability and productivity in large-scale building practices. The proposed design frees the 3DCP project from the limitation of the enclosure system and achieves a convenient printing and assembly process for the mushroom column and the ribbed slab. Admittedly, the feasibility of the proposed column-slab system still requires structural analysis and real-scale concrete printing tests to verify. Future research would also benefit from designing compression-only structures that align with the material properties of unreinforced concrete, thereby reducing rebar usage in large-scale concrete construction. In conclusion, the proposed method opens avenues for contemporary architects to explore more design concepts and typologies in concrete construction, showcasing the potential of 3DCP technologies in fostering diverse and sustainable cities through automated construction processes.

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