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Ultra-thin-layered 3D-printed hollow core sections for concrete casting

Mohsen VATANDOOST, Wes MCGEE, Peter von BUELOW*

*Taubman College of Architecture and Urban Planning, University of Michigan,
2000 Bonisteel Blvd. Ann Arbor, MI, USA.
pvbuelow@umich.edu

Abstract
Lightweight concrete shells with anticlastic curvature are among the most efficient structural systems. But the difficulty and cost of current construction methods present a challenge. This research employs additive manufacturing techniques to generate 3D-printed (3DP) hollow-core formwork for concrete casting. The additive manufacturing technique enables material to be put exactly where required; thus, less material is used, and material waste is significantly reduced. We propose utilizing a hollow-core section for the double-layered thin concrete shell to reduce the amount of concrete and increase the material efficiency. In the case study presented the first step is to tessellate the designed shell into smaller parts. This is done by considering the limitations of current robotic arms, available infrastructure, the transportation and moveability of a crane, and labor at the construction site. Also, the height of the parts and the wall thickness must be optimized based on the hydrostatic pressure of the wet concrete and formwork material properties. A trussed section is used to maximize mold stiffness with less material. Next, we use robotic 3DP to fabricate the formwork and cast and cure the concrete. Finally, since the shell is designed to act in pure compression, these parts can be assembled by friction-fit, without any glue or mortar, and with limited additional scaffolding. Additive manufacturing enables the production of custom formwork quickly and more accurately than traditional construction techniques.

Keywords: additive manufacturing, hollow-core section, thin-layer formwork, 3D-printed mold, robotic fabrication, lost formwork, stay-in-place formwork, eggshell formwork, thin-layer formwork, drop pan formwork, digital concrete

1. Introduction
On the one hand, global warming, climate change, and the carbon footprint are among the immense challenges that we face today. More than 35% of global energy consumption and over 40% of carbon emissions are attributed to the building industry and construction sector, as stated in the reports [1], [2], and [3]. On the other hand, population growth has been drastic in recent years, which means there will be more accommodation required [4]. These highlight the importance of adopting sustainable practices in construction.

The widespread availability of its components, combined with its strength, durability, and ability to be formed into any shape, elevates concrete to the status of the most widely utilized artificial building material on a global scale [5]. Furthermore, lightweight continuous concrete shell structures with anticlastic double curvature forms are among the most efficient structural systems [6]. The primary obstacle to implementing these structures is the complexity and expense of the existing construction techniques. 40–60% of the total cost of constructing a building may be allocated to formwork in concrete construction [7], [8], and 20–30% of construction waste is generated from discarded formwork [9]. Considering this, it is critical that we reevaluate our construction methods, as conventional formwork is not efficient. Utilizing additive manufacturing techniques, this study proposes a method for fabricating custom 3D-printed (3DP) hollow-core formwork for concrete casting of double-curvature, complex structures.

The objective of this study is to devise innovative computational techniques for fabrication that are appropriate for large-scale production. The additive manufacturing process permits precise placement of the material; consequently, significantly less material will be used and waste will be diminished. To reduce concrete consumption and increase the material's efficiency, we have proposed the utilization of a double-layered thin concrete shell incorporating a hollow-core cross-section.

2. Background

This research investigates and develops bespoke ultra-thin layered formwork to be utilized for the construction of complex forms. The 3D printed formworks provide geometrical freedom, material efficiency, and reduce material waste. The bespoke robotic-fused deposition modeling (FDM) technique that is implemented in formwork fabrication is currently an active research topic and requires some refinement before implementation.

Meibodi et al. [10] proposed a FDM formwork combined with a CNC laser-cut timber formwork to be used as a floor slab by using the formwork with casting and spraying concrete to make free-form shapes with very detailed surfaces. Jipa et al. utilized 3D-Printed disposable formwork [11] for a floor slab, in which the funicular ribs were following the patterns of principle stress. Similarly, Jipa et al. [12] developed a 3D Printed stay-in-place formwork for a 1.8 x 1 m slab that was optimized topologically. Here because the depth of the slab is significantly lower than other structural parts, e.g. columns and beams, the concrete pressure is less. Additionally, Meibodi et al. [13] studied a 3D printed, thin formwork to be applied for sandwich concrete walls, in their case study they produced a 2.4m tall x 2.0m curved concrete wall. Han et al. [14] used FDM printed formwork for façade panels, and were able to reuse the formwork several times. In a more recent research, Burger et al. [9] used a thin layered formwork for columns and slabs that were 3D printed.

To withstand the hydrostatic pressure of the concrete on formwork, Jiba et al. (ref) and Meibodi et al. [15] submerged the formwork in sand. Another method is to use a fast-setting concrete [16] in the process. Furthermore, Burger et al. [9], [17] employed a technique, 'digital casting', to control the casting process speed to reduce the hydrostatic pressure of the wet concrete on formwork, which is effective in pressure reduction. However, it makes the fabrication process more complex. Additionally, Tessmann et al. [18] used a 'rotational casting' technique, in which a minute volume of liquid (concrete) is poured into a mold and then rotated at a slow pace, causing the substance to spread evenly throughout the surface of the mold, this technique reduces the pressure on formwork. However, this technique has not been combined with FDM formwork yet.

As included in the literature review, the 3D printed formwork has not yet become widespread, and is not available on construction sites due to limitations in the technique This includes the slowness of the fabrication process and the fragility of the 3DP formwork which is not able to hold the hydrostatic pressure of the fresh concrete at large scale. In this research, the 3DP formwork is strengthened by making it double-layer with extra ribs added between layers (FIGURE 1, 2) to make it stiffer and able withstand the hydrostatic pressure of the concrete.

3. Materials and Methods

3.1. Materials

In this study, polymer extrusion, carbon fiber, PETG was used for the 3D printing process [19], [20] (Figure 3). The formwork made with this material can be ground and reused after concrete hardening, is removed. This makes it a very sustainable solution for concrete casting [13].

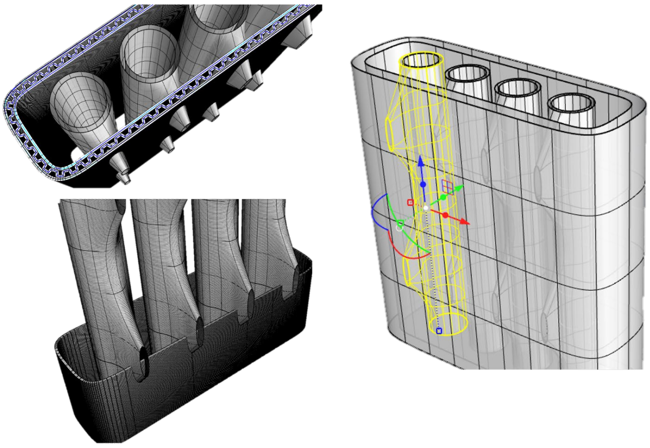

Figure 1. The computer image of the proposed formwork shows that the hollow cores will be achieved by inserting cylinders with a connection (bridge) to the outer form in order to hold them steady during the casting.

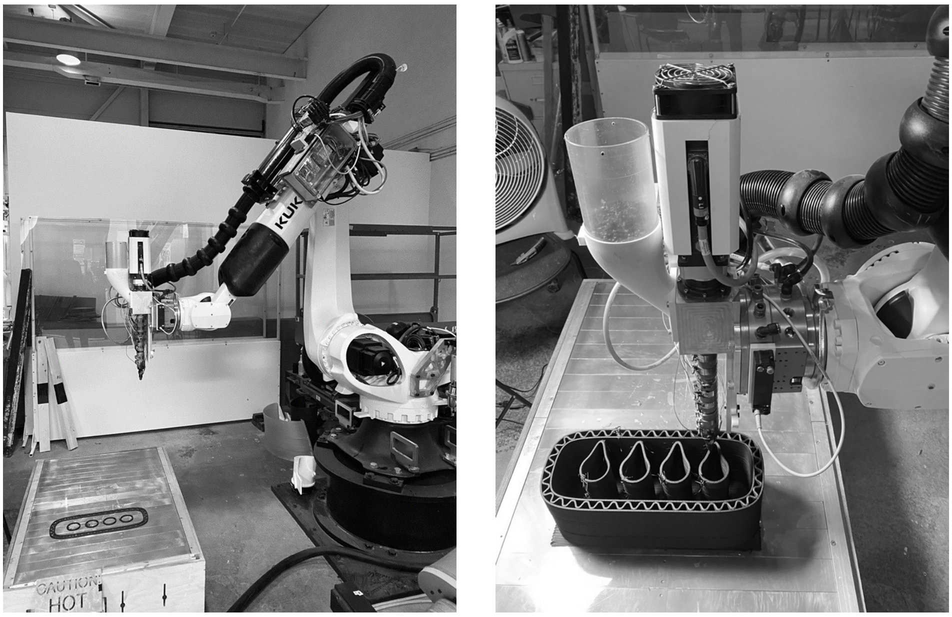

Figure 2. The additive manufacturing setup includes an extruder mounted on an industrial robotic arm (KUKA 120), which enables precise material placement, and a hot table as a base to provide stability during the printing process.

Figure 3. The basic material used for the 3DP is carbon fiber, and Polyethylene Terephthalate Glycol (PETG).

The Polyethylene Terephthalate Glycol (PETG) is an anisotropic material. The material properties are listed in Table 1.

Table 1: The material properties of the PETG used for 3D printing of the formwork.

Property	PETG
Density	1.7 gr/cm^3
Young's Modulus in print direction	10.5 Gpa
Young's Modulus in transverse	2.8 Gpa

3.2. Methods

As shown in Figure 4, the three phases of this investigation are as follows: design and optimization; robotic fabrication and assembly.

Design phase: Initially, the complex geometry of the double curvature ultra-lightweight shell is designed and optimized under specified conditions (e.g., loads and boundary conditions) and in accordance with selected objective functions and criteria, primarily structural performance. The computational morphogenesis method is utilized, which enables us to simultaneously explore and optimize the structure.

Fabrication phase: The next step is to tessellate the complex form of the double curvature, thin, lightweight shell into smaller, more manageable parts for fabrication. This is done by considering the limitations of current robotic arms' performance ranges, available infrastructure, the transportation and moveability of a crane, and labor at the construction site. Then an extruder mounted to a robotic arm is employed for the 3D printing of these parts that will serve as the concrete formwork.

An important thing is that the height of these parts and the wall thickness must be optimized based on the hydrostatic pressure of the wet concrete and formwork material properties. Based on these parameters, extra ribs are added to the sections. Furthermore, different tests are required to be able to determine the behavior of the formwork, including the formwork compression and flexural strength, leakage tests, and others. Finally, the robotic 3DP will be employed to fabricate the formwork (Figure 5).

In the next stage of the fabrication, the concrete is cast into the formwork and cured. It is crucial to find a proper concrete mixture (e.g., Engineered Cementitious Composites (ECC); and ultra-high-

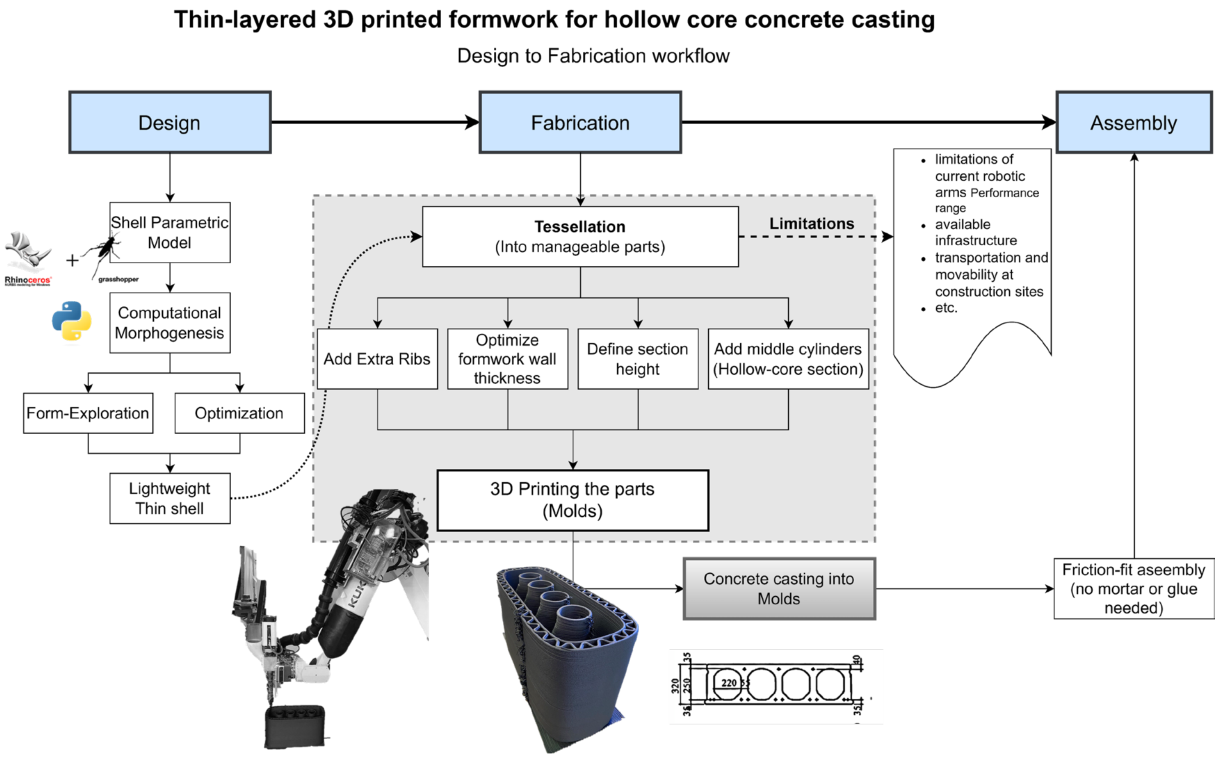

Figure 4. The investigation consists of three phases: design and optimization, robotic fabrication, and assembly

performance fiber-reinforced concrete) used in combination with the formwork to produce the highest efficiency and desired strength.

Assembly phase: Finally, since the shell is designed to act in pure compression, these parts can be assembled as friction-fit, without any glue or mortar, with limited additional scaffolding.

The steps of this investigation are summarized below:

Generate the 3D advanced parametric model of the complex form (e.g., double curvature, lightweight shell structure), then utilize computational morphogenesis, which combines form-exploration and optimization to achieve an integrated workflow that encounters design and fabrication. Next, tessellate the form into manageable parts and optimize the height and the wall thickness of the formwork based on the hydrostatic pressure of the wet concrete.

Hydrostatic pressure refers to the force exerted by newly poured concrete on the formwork, measured per unit area [13]. The hydrostatic pressure acting on each point of the formwork, Eq. (1), is defined by the vertical distance and the density of the casting fluid above that point.

$$P = \rho g d \tag{1}$$

P is Hydrostatic pressure, ρ is the density of the fluid (concrete), g is gravitational acceleration, and d is the depth below the surface on the formwork, where the pressure is calculated.

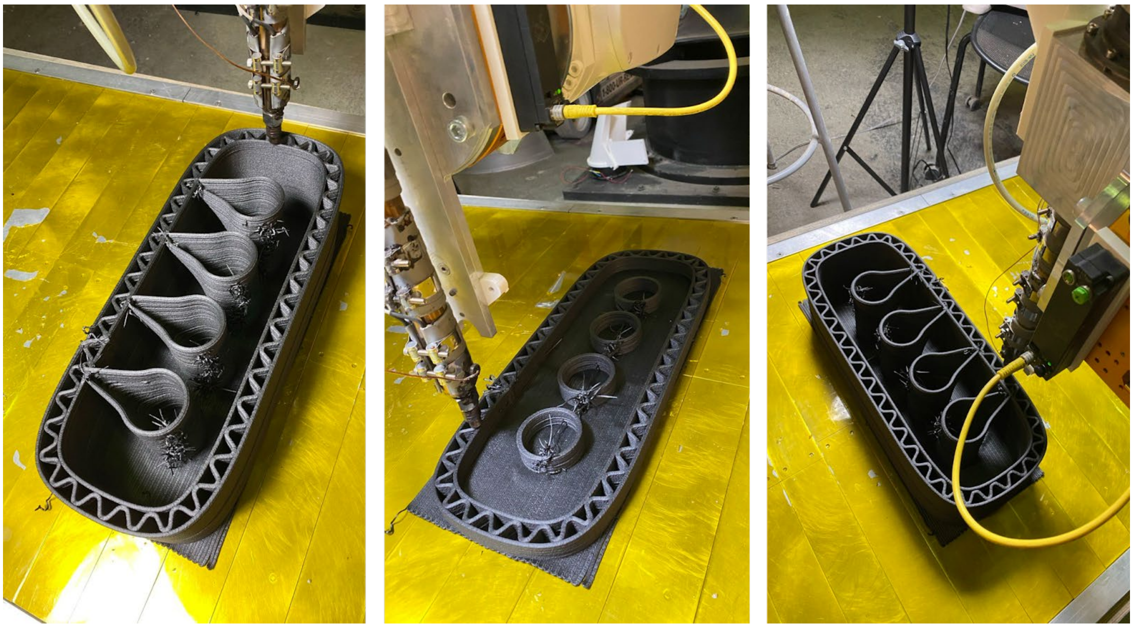

Figure 5. The initial prototyping of the proposed formwork by additive manufacturing techniques and utilizing carbon fiber as the material for 3DP

Then, the sections of formwork are 3D printed and subsequently physically tested. Different material should also be tested for the formwork. The next step is to cast the concrete into the formwork and cure it. It is required that different types of concrete (ECC, ultra-high-performance fiber-reinforced concrete), be physically tested and evaluated to achieve maximum performance, and minimum carbon foot-print. After removing the formwork, these parts will be assembled without any mortar or glue, with limited scaffolding. To demonstrate the validity of this workflow, a case study of the design and fabrication of an ultra-lightweight concrete pavilion as a full-scale architecture project utilizing 3D printing for the formwork is carried out, and a part of that is created in this study.

4. Results and discussion

An initial prototyping of the proposed formwork by additive manufacturing techniques and utilizing carbon fiber as the material for 3D Printing is depicted in Figure 6, and the casting process is depicted in Figure 9. The formwork has strength enough to withstand the wet concrete hydrostatic pressure, with no visible deflection. In addition, no leakage was observed during the casting process (W/C Ratio was 22.5%). The mixture and properties of the concrete are provided in Table2.

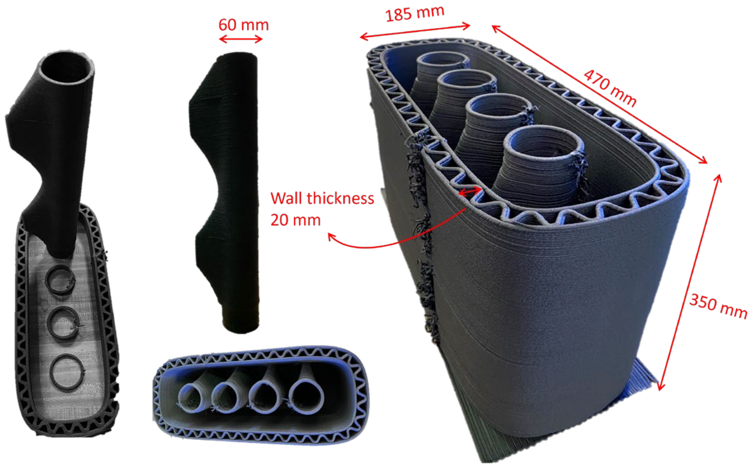

Figure 6. The initial prototyping of the proposed formwork by additive manufacturing techniques and utilizing EPEG as the material for 3D Printing

The 3D printed formwork performance was studied and evaluated by an actual test on the 3D printed formwork. For this purpose, we tested several samples with the different materials that we have used for 3D printing. Figure 7 shows the test configuration.

As displayed in Figure 7, the strength test setup and breaking point of the tested samples revealed that although the carbon fiber has a significant strength, it did not show much plasticity. The force-displacement graphs of the 3D printed formwork for different specimens are provided in Figure 8. The Carbon Fiber, PETG and mixture of these two were used.

Based on the strength test results as depicted in Figure 8, nine specimens were tested. Four of these were made of carbon fiber (marked as CF in the graph). The maximum axial force that these samples could withstand was around 3.5 KIP (1587 kg), which was close to the PETG samples. However, the PETG samples were more flexible, and for applied loads showed more displacement compared to the carbon fiber specimens. In another words, the PETG in comparison to carbon fiber has lower value for the Young's modulus.

Figure 7. The strength test setup and tested samples

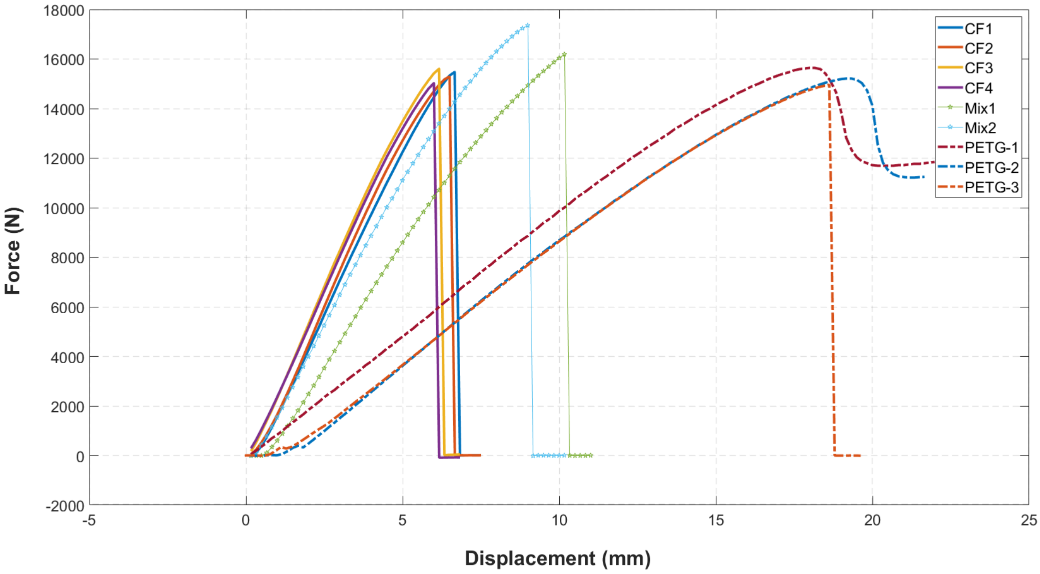

Figure 8. The force-displacement graphs of the 3D printed formwork, for different specimen are provided; the Carbon Fiber, PETG and mixture of these two were used

Furthermore, some specimens were printed and tested by combining carbon fiber and PETG (marked "mix" in the graph), with the weight combination of 80 to 20 percent (CF to PETG). As it is plotted in the above graph, the mix samples performed better, and could withstand nearly 10% more force, 3.9 KIPS (1769 kg), while the displacement to force was increased in comparison to carbon fiber samples and decreased to PETG samples. Thus, finding a mixture of these two materials (or other materials) to reach a composite that can withstand much more force while providing enough flexibility will be an open question, which we intend to address in our ongoing research on this topic.

Next, we cast concrete into formwork. The concrete was made of Portland Type IL, Portland-limestone cement (PLC), which is engineered with a higher limestone content to reduce the carbon footprint of concrete [21]. The water-to-cement ratio (W/C) was chosen as 22.8%. The detail of the mixture is provided in Table2.

Table 2: The concrete mix (per liter) used in this study with the water-to-cement ratio (W/C) of 22.8%.

Ingredients	Weight (gr)
Portland Type IL	350
Fly Ash	480
Silica Fume	57
Medium Sand	530
3/8" Gravel	500
Polycarboxylate HRWR	4
Viscosity Modifier (VMAR)	4
H_20	190

The demolding process was done without much effort by using an electric saw due to the use of release inside of formwork before casting concrete. Finally, the concrete hollow-core section after demolding is displayed in Figure 10 Part of the formwork will remain as a lost formwork intentionally (the cylinders). The formwork will be ground to be reused. The demolding process did not damage the concrete surface, and the quality of the finished surface is high (Figure 10).

Figure 9. The casting process of the 3D printed formwork; the formwork was strength enough to withstand the wet concrete hydrostatic pressure, with no visible deflection. In addition, no leakage was observed during the casting process (W/C Ratio was 22.5%).

Figure 10. The concrete hollow-core section after demolding; part of the formwork will remain as a lost formwork intentionally (cylinders). The formwork will be ground to be reused. The demolding process did not damage the concrete surface, and the quality of the finished surface is high.

5. Conclusion

The goal of this research was to advance the fabrication method of complex geometries by employing additive manufacturing, the 3DP technique, and hollow-core sections. The 3DP formwork has not yet become widespread due to some limitations in the technique including the slow speed of the fabrication process, the small scale of the printed parts, and the strength of the 3D printed formwork to support the loads at architectural scale.

In this research, one of these limitations was addressed by improving the formwork, making it double-layered and adding extra ribs as well as using a truss-based section to maximize mold stiffness with minimum material. In addition, the whole structure is tessellated into smaller manageable parts, within the current robotic arms performance range, and after casting the concrete into those parts, the hardened part will be assembled by friction-fit without any glue and mortar, therefore fabricating architectural scale structures will be possible. Furthermore, hollow core sections were used which have less material consumption, and address the carbon footprint, however, further research on this topic is required.

In addition, after the concrete has hardened, this 3DP formwork can be removed, ground, and recycled. Therefore, material waste is reduced significantly. In addition, these 3DP formworks are reusable and can address the global warming, CO2 emissions challenges in the building industry [13], [3],[22].

The use of 3D printing technology for creating formwork for concrete has the potential to provide a solution to climate change and carbon footprint issues. It may enhance geometric flexibility, leading to construction methods that use materials more efficiently and reduce waste from the formwork. This research has the potential to make significant contributions to state-of-the-art projects and influence the development of advancements in digital building technologies. The additive manufacturing technique might enable us to produce custom formwork with complex geometries quickly, accurately, and in greater quantities with significant advantages compared to traditional construction techniques, which are costly, time-consuming, labor-intensive, and cause tremendous material waste.

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Author(s): Mohsen VATANDOOST, Wes MCGEE, Peter von BUELOW

Affiliation(s): Taubman College of Architecture and Urban Planning, University of Michigan,

Address: 2000 Bonisteel Blvd. Ann Arbor, MI, USA.

Phone: +49 734 763 4931

E-mail: pvbuelow@umich.edu

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