Technical Analysis and Comparison of Formwork-Making Methods for Customized Prefabricated Buildings: 3D Printing and Conventional Methods

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Abstract: Three-dimensional (3D) printing technology is increasingly playing an essential role in the customization of prefabricated buildings. To demonstrate its high-quality, cost, and time-saving advantages, this paper first presents a technical analysis of prefabricated formwork-making using 3D printing. Then, we compare 3D printing to the two conventional methods of manual wood and computer numerical control (CNC) foam using a demonstration house with curved walls specially designed and constructed using these three formwork-making methods. We concluded from our comparison that the 3D-printed polymer-based formwork-making method performed best in accuracy and time, and generated greater cost-effectiveness than did the manual wood and CNC foam formwork-making methods for the mass production of customized prefabricated buildings. Lastly, this paper provides design guidelines for architects to help achieve the highest economic savings and efficiency in customized prefabricated formwork utilizing the 3D printing method. **DOI: 10.1061/(ASCE)AE.1943-5568.0000397**. *© 2020 American Society of Civil Engineers*.

Author keywords: 3D printing; Formwork-making; Prefabricated building; Mass customization.

Introduction

The practice of customized buildings has become a worldwide blossoming trend; extremely impressive forms are rebuilding the skylines of cities with dazzling exteriors and striking structures (Han et al. 2019). This free-form architectural design style, containing a multitude of irregular shapes, has gained substantial interest from contemporary architects. However, realizing the complexity of the diverse forms and geometries in free-form design has created the urgent need for developing formwork-making methods to improve the construction productivity and cost of such customized buildings.

The most common method used for constructing these customized buildings is assembly of the building components in a manufacturing facility, known as prefabrication. The alternative to this process is onsite fabrication, in which the fabrication process takes place at the location of the construction. There are several conventional prefabrication formwork-making methods [e.g., manual, computer numerical control (CNC), vacuumed/pressurized, and metamorphic]. The manual method uses wooden materials, such as plywood or knitted textiles (West and Araya 2009). The CNC method utilizes a computer to accurately mill, cut, and bend materials such as metal, plastic, stone, and expanded polystyrene (EPS) into the formwork shapes. The vacuumed/pressurizedmethod can either vacuum/inflate foils or textiles to construct the formwork (Schipper and Eigenraam 2016); however, although textile material yields molds that are lightweight, flexible, and easy to remove, they are unable to ensure an equal thickness of the applied material and suffer from the precision of the specific angles of geometric segments. (Buswell et al. 2007; Lee 2008). The metamorphic formwork method uses numerical control rods (NCRs) or a pin-bed machine to obtain customized molds for phase-change materials, such as paraffin, rubber, thermoplastic composite materials, and memory alloy metals (Verhaegh 2010; Ryu and Kim 2012), which render a rapid prototyping environment often resulting in small size limitations and high costs that are directly associated with the machines and materials used throughout the fabrication process.

Recently, a new method, the process of three-dimensional (3D) printing, has been explored for the creation of highly complex geometry using polymer-based materials (Yin et al. 2018). 3D printing manipulates an object in its digital format by adding the materials in a sequence of layers, each of which is printed directly on top of the previous layer. This process also is known as additive manufacturing (AM), and has become an increasingly common method for customized prefabricated components in buildings (ASTM 2010). In a mass customization scenario (i.e., in which a component is repeated numerous times), it is more feasible and cost-efficient to prefabricate a component with 3D-printed formwork than to directly print the desired component (Buswell et al. 2007; Hack and Lauer 2014). For the professionals of the architecture, engineering, and construction (AEC) industry within a large-scale building construction scenario, the prefabrication process is a less aggressive and more practical solution than using the onsite fabrication process. Unlike the style decisions of contemporary architecture, these prefabrication versus onsite fabrication decisions

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can be seen extensively in the free-form architectural style, which is currently in the experimental and conceptual review stage (Kim et al. 2015). Due to the current technical limitations of free-form architecture, producing customized building components has many challenges in quality, cost, and durability. Therefore, few previous studies have been able to quantitatively compare the essential performance (accuracy, cost, and time) of different formwork-making methods for the prefabrication of customized concrete components.

Using a demonstration house of the free-form architectural style that was constructed for the 2018 China Solar Decathlon Competition, the study presented in this paper analyzed the technical strengths, features, and attributes of utilizing 3D-printing methods for the fabrication of formwork for its customized components. The study focused on attributes of the 3D-printed formwork method that included accuracy, cost, and the number of repetitions in which the formwork was used for casting. These attributes were then compared in a technical analysis to the two primary conventional methods of the formwork-making process: manual wood formwork and CNC foam formwork. According to the results of this quantitative analysis, the best formwork-making method for the mass production of customized building components was distillation. This paper concludes with design guidelines recommended for architects to help them achieve the highest economic savings and the highest efficiency using the 3D-printing method for customized prefabricated building components.

Literature Review on the Three Formwork-Making Methods

Requirements of Formworks for Concrete Casting

The material used in building-component casting processes is concrete, which is a mixture of cement (9%–15%), water (15%–16%), and fine to coarse aggregates (25%–35% and 30%–45%, respectively) (Schwoon et al. 2013). Once the material components are mixed, the concrete loses viscosity due to the addition of water, which enables it to be poured into a fabricated formwork that serves as the mold of the desired component's geometry. After the concrete has been poured into the formwork, it is *set* through the exothermic reaction of the concrete components resulting in the curing process. Owing to the characteristics of the material, as well as the average density being 2,400 kg/m^3, about 2.5 times that of water (Schwoon et al. 2013), there are several requirements for the formwork. These requirements are that the formwork must sustain the outward pressure of the concrete by not changing shape during the casting process and it must be nonporous, waterproof, and nonreactive to the curing process.

Performance Comparisons among Different Formwork-Making Methods

The technical and managerial limitations of producing customized prefabricated buildings has always led to problems associated with the three main performance aspects of formwork: accuracy, cost, and time (Lee 2008). These three aspects of formwork-making not only help architects select the contractors and formwork-making method but also directly influence the design of the building through the levels of customization and complexity of the possible components (Karke and Kumathekar 2014). The performance of a chosen formwork-making method may depend on several factors, ranging from the formwork material to the manual skills associated with the machine and fabrication procedures (Ganar and Patil 2015). The next part of this literature review discusses the studies most relevant to the performance of the three formwork fabrication methods.

Durability

The structural durability of wood formwork is not strong enough to hold the weight of more than 12 in. of concrete (Ganar and Patil 2015) and must be sealed to prevent water leakage. CNC foam formwork, unlike the manual wood method, is waterproof and rigid but is still susceptible to breaking or crushing (Karke and Kumathekar 2014). The density and compressive strength of a 3D-printed, polymer-based (ABS with carbon-fiber reinforcement) formwork is much higher than that of either wood or foam (Yin et al. 2018). According to a test report from one of the leading companies in precast concrete manufacturing, a 3D-printed formwork can be reused for as many as 200 concrete pours within its lifetime (Hendrixson 2018a). On the other hand, the lifetime of wood and foam formworks are approximately 20 and 10 pours, respectively, while serving as a precast concrete formwork (Hendrixson 2018b). Whereas both the wood and foam require intensive repair work after each cycle of the precast concrete pour, the 3D-printed formwork provides excellent durability with only minimum maintenance effort after each concrete pour.

Accuracy

Due to the high degree of automation, the CNC and 3D-printed formwork-making methods are more accurate than the manual method of wood formwork (Carrillo et al. 2017; Yin et al. 2018). However, all three methods lead to rough surfaces and require a postprocess surface treatment, such as polishing or plastering, to obtain better accuracy.

Making Cost

The manual wood formwork-making method is a traditional method, for which the cost of precasting the concrete components in a lifespan of few casting repetitions is low. The CNC foam formwork-making method is also cost-efficient and widely used because of its labor efficiency and the universality of CNC machines (Prajapati et al. 2014). However, both the manual wood and the CNC foam formwork-making methods have an additional cost for maintenance due to their low durability. Making a 3D-printing formwork is still costly for one-off casting situations because of the machine and material expenditures (Peters 2014); however, its formwork becomes cost-effective when used repeatedly.

Time Consumption

The three formwork-making methods are more time-consuming than the flexible methods, such as the vacuum/pressurized and metamorphic formwork-making methods (Verhaegh 2010; Ryu and Kim 2012; Schipper and Eigenraam 2016). The CNC and 3D-printing methods have a high degree of automation and can run over periods of hours to days. However, the time consumption of the manual methods is generally greater per mold as they require manual labor, which is dependent on the skill and proficiency of the workers. Table 1 is a summary of our performance comparison between the three formwork-making methods.

Many of the previous performance comparison studies of the formwork-making processes focused on a qualitative analysis of components with regular-form geometry, which are not comparable to free-form shapes. The primary quantitative research of curved prefabricated components shows that, unlike regular forms, they are made in a laboratory environment. The mechanical properties of the formwork materials are used to decide the quality and durability of the formwork for concrete casting (Carrillo et al.

Table 1. Performance comparisons of the three formwork-making methods

	Formwork-making method		
Parameter	Manual	CNC	3D-printed
Material	Wood	Foam	Polymer
Procedure	Cutting, fabricating	Milling, bending, cutting, polishing	Printing, polishing
Degree of automation	Low	Medium	High
Manual skill requirement	High	None	None
Density (kg/m^3)	500–650	12–32	1,130
Compressive Strength (psi)	3,900–8,500	25	16,000
Durability	Low	Low	High
Making accuracy	Low	High	High
Making cost	Low	Low	High
Making time	High	Medium	Medium
Waste of material	High	High	Low
Customized level of form	High	Medium	Medium

2017). Since 3D printing is an emerging technology for formwork-making, very few of the existing studies conducted a performance comparison between the traditional and 3D-printing methods. This study therefore focused specifically on such an analysis and comparison of the three formwork-making methods utilizing customized curvilinear free-form building components. A real design-and-construction project with a highly complex curved shape was utilized to assess the performance of 3D printing with the most potential for formwork-making, prioritizing the free-form building components.

Methodologies

Demonstration House Project

In the summer of 2018, our demonstration house was designed and constructed during the Solar Decathlon Competition in China. The inspiration for the architectural design was the lotus flower, which is the natural symbol of purity and elegance. Its free-form petals were abstracted as curving walls. Its rounded planar shape was reasonable for detailing as the layout for a residential house inspired by an organic design concept from Frank Lloyd Wright. By using 3D-printing technology in the areas of architectural design and construction, the project aimed to demonstrate a house that was innovative, attractive, and sustainable as shown in Figs. 1 and 2. The free-form demonstration house was composed of 12 parabolic-shaped exterior walls, as depicted in Fig. 3.

Each panel wall consists of a glass-fiber-reinforced concrete (GFRC) outer shell and a glass-fiber-reinforced-gypsum (GFRG) inner shell with a cavity between the shells filled with a steel skeleton and an insulation material. The paneled walls have similar shapes but are different in size, rendering each unique. The roof is composed of eight double-curve, pitched composite panels with the same construction as the exterior wall panels.

Fabrication of the Customized Components of the Demonstration House

The initial objective of the demonstration house was to print a complicated organic form directly on the site to demonstrate that 3D printing can enable the mass customization of a house. In

Fig. 1. Overall aerial view of the demonstration house. (Image by Dongchen Han and Hongxi Yin.)

Fig. 2. Night side-view of the demonstration house. (Image by Dongchen Han and Hongxi Yin.)

Fig. 3. Shell wall construction of the demonstration house. (Image by Dongchen Han and Hongxi Yin.)

consideration of the low repetition of the customized components, the urgent schedule for construction, and the low budget, the project managers decided to adopt the manual and CNC formwork-making methods to produce the building components. The 3D-printing method was tested with a sample formwork for the analysis and comparisons.

A polymer-based formwork made with 3D printing was used in precasting one of the GFRC wall panels for proof of concept. The big-area additive manufacturing (BAAM) system was used with a formwork material of 20% carbon fiber with reinforced ABS polymer. After the formwork was printed, a CNC milling machine polished the formwork's surface. This study developed and tested the other two formwork-making methods for quantitative comparison between them and the 3D-printing technology. A manual wood formwork-making method was used to fabricate the shell panel walls, as shown in Fig. 3. A CNC machine was used first to cut nominal wooden boards to the hundreds of finished pieces. Woodworkers then assembled the small wooden pieces to form the 3D shape and finished the formwork with epoxy plaster to make the smooth 3D surfaces. A CNC machine made the foam formworks for the roof panels using two steps (cutting and milling). Table 2 is a summary of the three formwork-making methods used in the demonstration house.

This study compared the performances of these three methods with respect to their accuracy, cost, and time. Accuracy and time were measured and recorded by the authors; the durability information over the lifespan per mold was acquired from the related literature and AEC companies; and the fabrication costs were provided by the construction contractors for the demonstration house.

3D Laser Scanning for Measurement and Accuracy Comparison of Formwork Surfaces

3D laser scanning is an active-range-based reverse engineering (RE) technology for measuring the feature dimensions of a desired target. This process produces a 3D digital representation by illuminating the target with a pulsed laser light and detecting the reflected pulsed light with a sensor (Mateus and Ferreira 2013). This study used 3D laser scanning to examine the final finishing of the formwork surfaces of the three methods and then reconstructed their as-built models digitally to obtain the measured parameters for the accuracy analysis.

The measuring tolerance of the 3D laser scanning device was at the magnitude of a millimeter and with the specific range error determined by the selected scanner model (Lague et al. 2013). This study used a portable scanner with an error range of around 0.12 mm (technical specifications of HandyScan 3D, Creaform 2019) for the surface measurement and digital reconstruction of the wood formwork, as shown in Fig. 4. A terrestrial laser scanner (TLS) with a range error of less than 1 mm (Trimble TX8 Laser Scanner Datasheet 2014) was used for the foam and 3D-printed formworks, as shown in Fig. 5.

The accuracy of the three formworks was measured by the deviations between the as-built and as-design models (Palikhe et al. 2018). A comprehensive metrology software for quality inspection was used to produce the deviation analysis of the size, shape, and location with graphics and data tables, which explicitly showed the accuracy of the different formwork-making methods.

Table 2. Three formwork-making methods in the demonstration house project

Parameter	Making method: Manual wood formwork	CNC foam formwork	3D-printed polymer-based formwork
Application	Formworks of all shell wall panels	Formworks of all roof panels	A sample formwork of the shell wall panel
Machine	CNC cutting machine, wood-working tools	CNC cutting and milling machine	BAAM system, CNC milling machine
Material	Wood board, fiberboard, epoxy plaster	Rigid EPS foam, epoxy plaster	20% carbon fiber with reinforced ABS polymer

Process of the Three Formwork-Making Methods

Manual Wood Formwork-Making Method

Many prefabricated projects make use of wood formworks, especially for formworks that are not economically feasible for steel formworks due to low repetition or complex shapes (Schipper and Eigenraam 2016). The exterior walls of the demonstration house were made using this method. The manual wood formwork-making method combines traditional and modern techniques. Depending on the complexity of the shape, the manual wood formwork-making method is a labor- and equipment-intensive process and can be compared to that of boat carpentry. This method consists of four steps: digital modeling, CNC cutting, formwork fabrication, and surface treatment as shown in Fig. 6. The details of each step follow in the next sections.

Fig. 4. Surface scanning of formworks by the portable scanner. (Image by Dongchen Han and Hongxi Yin.)

Fig. 5. Surface scanning of formworks by the TLS. (Image by Dongchen Han and Hongxi Yin.)

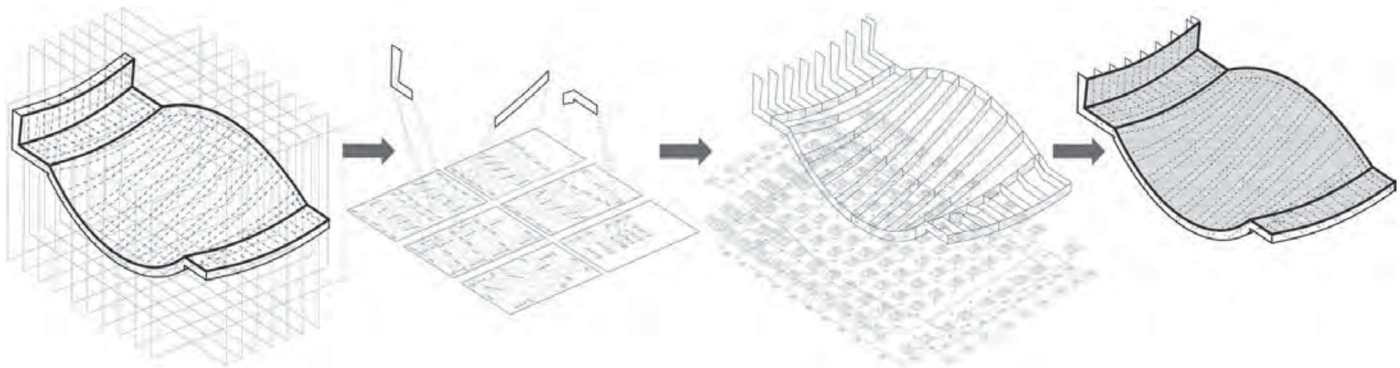

Fig. 6. Process of the manual wood formwork-making method: digital modeling, CNC cutting, formwork fabrication, and surface treatment.

Fig. 7. CNC cutting. (Image by Dongchen Han and Hongxi Yin.)

Fig. 8. Fabrication of the structure part. (Image by Dongchen Han and Hongxi Yin.)

Fig. 9. Fabrication of the surface part. (Image by Dongchen Han and Hongxi Yin.)

Fig. 10. Plastering, sanding, and painting. (Image by Dongchen Han and Hongxi Yin.)

Step 1: Digital Modeling. The first step was the translation from file to factory. The Rhino model of the wall panel surface was transferred to a composite of many two-dimensional (2D) longitudinal frame pieces. All the details (x, y, and z coordinates) of the frame pieces were labeled. Then, 2D computer-aided-design (CAD) data were exported directly from Rhino to a CNC machine.

Step 2: CNC Cutting. A CNC machine was used to cut the longitudinal frame pieces from wood, fiberboard, or plywood board as shown in Fig. 7. For the demonstration house, each formwork for one wall panel contained about 30 longitudinal frames.

Step 3: Formwork Fabrication. The formwork fabrication included framing and planking. The longitudinal frame pieces were first lined up on a flat surface marked with the coordination points and lines, which were clamped together like the beams of a boat. Once the skeleton was made as shown in Fig. 8, only minor adjustments to the angles of the cuts were required. The frame was then nailed together with reinforcing edge pieces to sustain the loads of the concrete and operators. This hull, or curved

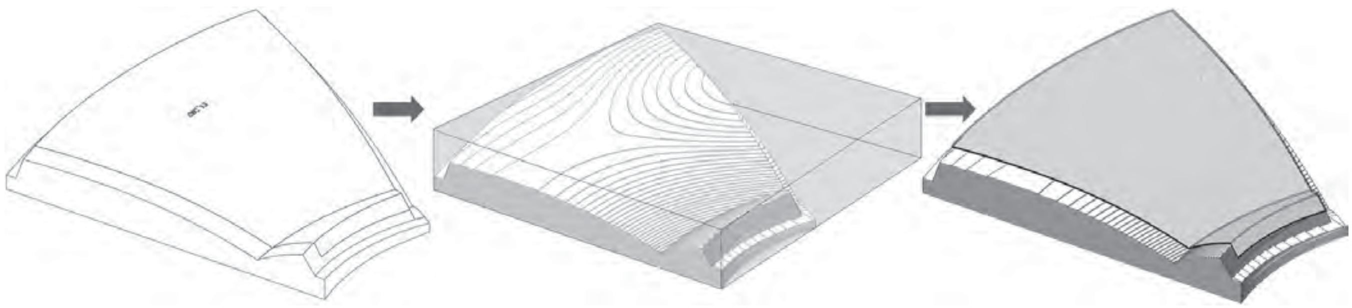

Fig. 11. Process of CNC foam formwork-making method: digital modeling, CNC milling, and surface treatment.

Fig. 12. The CNC machine and foam block. (Image by Dongchen Han and Hongxi Yin.)

Fig. 13. CNC coarse milling. (Image by Dongchen Han and Hongxi Yin.)

Fig. 14. After CNC fine milling. (Image by Dongchen Han and Hongxi Yin.)

Fig. 15. Plastering and polishing separately. (Image by Dongchen Han and Hongxi Yin.)

surface of the formwork, was then made by attaching plywood panels along the curve of the longitudinal frame pieces as shown in Fig. 9. These plywood panels were made from the same piece of wood to ensure uniform bending force. For the twist in the surface, which was quite large, more plywood pieces were required. When the hull/curved surface was created, the plywood expansion caused warping and cracking on the edges of the deck, which needed extra adjustments.

Step 4: Surface Treatment. The surface treatment step included plastering, sanding, and painting. The entire surface of the hull/curved panel was patched with 30-mm epoxy plaster/putty. After the plaster was dry, the cover was sanded, as shown in Fig. 10. Moreover, the edges and corners were reinforced with fiberglass tape. The sanding was challenging because of the curved angles and small dead-ended spaces, and several epoxy plaster coats therefore were needed in some areas to make a perfectly smooth surface. The high quality of the finishing work was primarily achieved by hand and with repetitive sanding with an orbital sander. Finally, the finished surface was coated with a layer of wax designed for demolding the concrete from the formwork surface. After the wax had cured for 24 h, the formworks were ready for making GFRC panel walls.

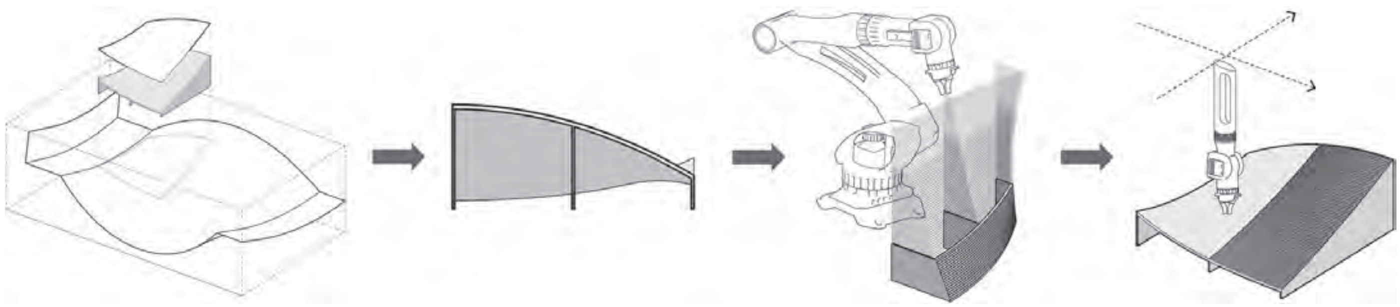

Fig. 16. Process of 3D-printed polymer-based formwork-making method: design modeling, model adjusting, 3D printing, and CNC smoothing.

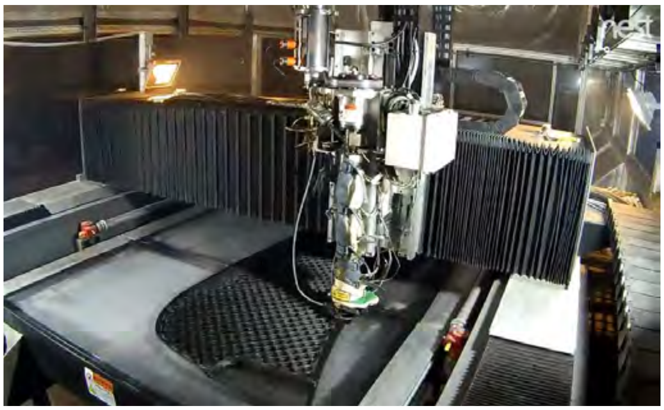

Fig. 17. 3D printing. (Image by Austin Schmidt, AES.)

Fig. 18. CNC smoothing. (Image by Austin Schmidt, AES.)

CNC Foam Formwork-Making Method

Like the wall panels, the roof panels were all unique and were a final desired material of GFRC. These panels were cast using CNC formworks with rigid EPS foam as the formwork material. The process of this CNC foam formwork-making method included digital modeling, CNC milling, and surface treatment as shown in Fig. 11.

Step 1: Digital Modeling. First, the engineer transferred the digital roof-panel model to the required format for the CNC machine via CNC software.

Step 2: CNC Milling. A large CNC machine milled the firm foam blocks in two stages as shown in Fig. 12: first, coarse milling was done as depicted in Fig. 13 and then fine milling as shown in Fig. 14. To reduce waste materials, three blocks of foam were used for one integral block for CNC milling of one component. In the coarse milling process, the depth of each milling pass for the first stage was about 10–15 mm, whereas the thickness of each milling for the fine milling process was about 5 mm. The milling process of the two stages took nearly 12 h.

Step 3: Surface Treatment. The treatment involved manually covering the surface with 30-mm epoxy plaster and then sanding the top layer for perfect smoothness. This step was the same as that for the manual wood formwork-making in Fig. 15.

3D-Printed Polymer-Based Formwork-Making Method

To analyze the 3D-printing method, a sample formwork of the exterior GFRC shell wall was printed. As shown in Fig. 16, the 3D-printed polymer-based formwork-making method included four steps: (1) digital design modeling in Rhino, (2) model adjusting according to 3D-printing process, (3) printing by 3D printer, and (4) smoothing by CNC. Using a commercial BAAM service provider, the proof-of-concept formwork was printed. This was considered a cost-effective fabrication of large 3D parts (Roschli et al. 2018).

Step 1: Design Modeling. The process started with the selection of a GFRC outer wall panel designed in Rhino. A partial piece of this panel was selected which represented the maximum complexity of the panel's curved surface.

Step 2: Model Adjusting. Due to the nature of the 3D-printing process, it was necessary to produce the selected component horizontally; thus, additional supports were added to the model to reduce the risk of printing failure. Because the print consisted of an outer shell, an infill or supporting structure for the formwork was added to ensure the formwork was able to structurally hold the GFRC. The digital model was exported in a stereolithography (STL) file format, which was native to CAD software. The STL file was then imported into a slicing software that resembled the CNC tool-path-creation software, which was a custom software specifically designed to work with the BAAM printer model. Finally, the 3D-printing process was simulated in the built-in BAAM software to ensure that the developed tool path was workable.

Step 3: 3D Printing. In this step, the sample formwork was built layer by layer, by depositing a material composed of ABS polymer with 20% carbon fiber. Extrusion deposition (ED) is the crucial process of 3D printing by making the most of the low melting point, low distortion, and anisotropic mechanical properties of the polymer-based material (Yin et al. 2018). The BAAM system operated off a gantry-style system and extruded the melted composite in a series of layers, as depicted in Fig. 17.

Step 4: CNC Smoothing. After being printed, the rough surface due to the successive layers of ED was smoothed by a CNC machine, as shown in Fig. 18. Unlike the other methods, the smoothed polymer-based formwork allowed for demolding the concrete from

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the formwork with no need for plastering. As illustrated in Figs. 19 and 20, half of the sample formwork was milled to the as-built state and the other half was kept in its original as-design state. The quantitative comparison between the as-design model and the as-built model confirmed the accuracy of the 3D-printed formwork both before and after smoothing.

Results and Discussions

Making-Accuracy Comparison

Figs. 21–29 depict the accuracy comparison of the three formwork-making methods. Figs. 21, 24, and 27 are the *as-design* models generated from the original Rhino designs. Figs. 22, 25, and 28 are the *as-built* models generated from the scanning data point clouds. Figs. 23, 26, and 29 depict the accuracy analysis of the fabrication process, which was the comparison between the two models. These diagrams represent the extent and location of deviations in the lines of two orientations from −10 to +10 mm, with gridlines representing the maximum level of similarity with a range from −0.5 to +0.5 mm. In general, the most significant deviation was observed at the location of the maximum curvature.

Figs. 30–33 are the plotted deviations between the as-design and as-built models for the three methods and include both the postprocess milled and unmilled examples for the 3D-printing method. The error distributions for CNC and milled 3D printing were normal

Fig. 19. The completed formwork. (Image by Dongchen Han and Hongxi Yin.)

Fig. 20. Half-milled surface of the formwork. (Image by Dongchen Han and Hongxi Yin.)

Fig. 21. As-design model of manual formwork.

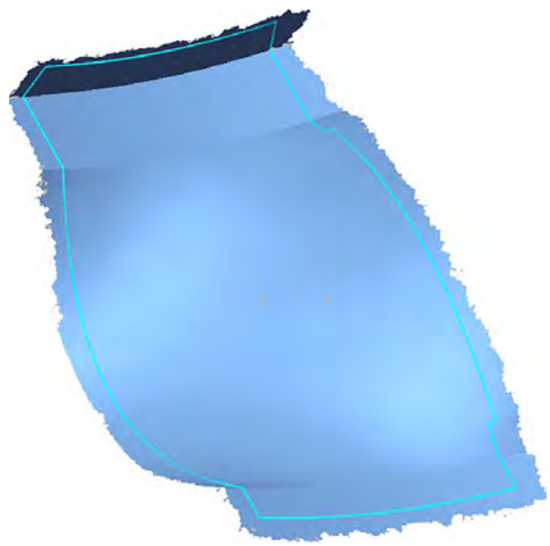

Fig. 22. As-built model of manual wood formwork.

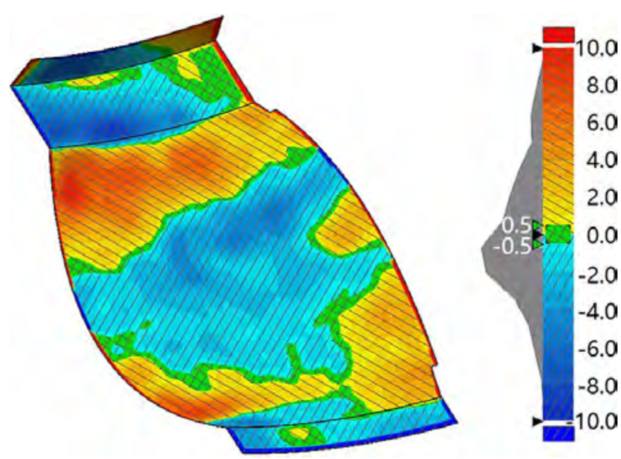

Fig. 23. Accuracy analysis results of manual wood formwork (mm).

Fig. 24. As-design model of CNC foam formwork.

Fig. 25. As-built model of CNC foam formwork.

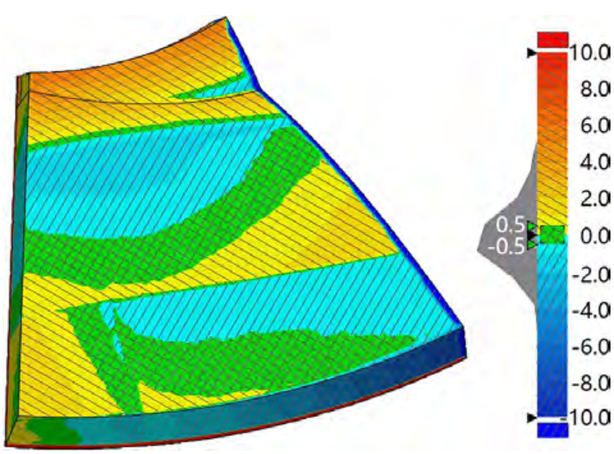

Fig. 26. Accuracy analysis results of CNC foam formwork (mm).

Fig. 27. As-design model of 3D-printed formwork.

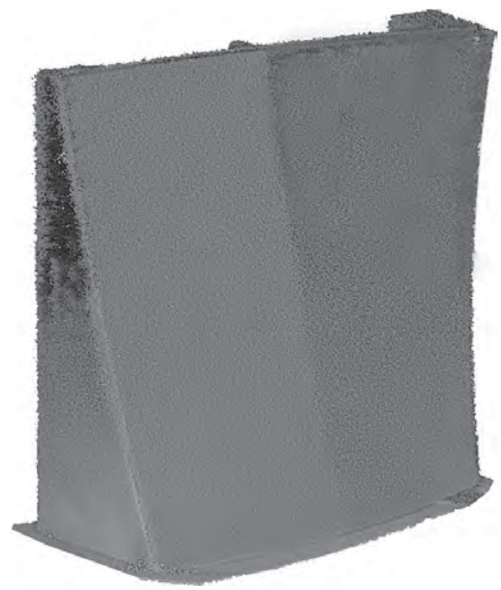

Fig. 28. As-built model of 3D-printed formwork.

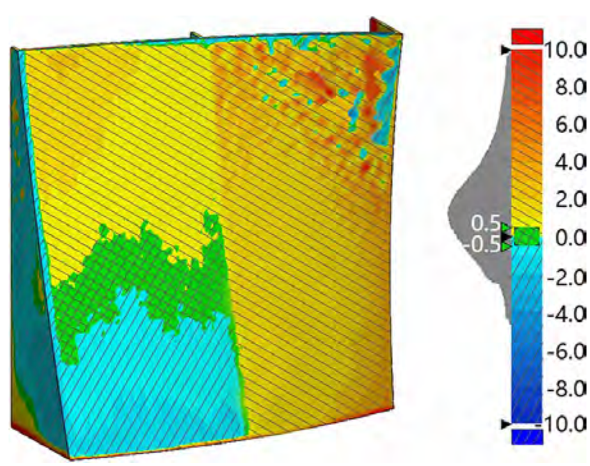

Fig. 29. Accuracy analysis results of 3D-printed formwork (mm).

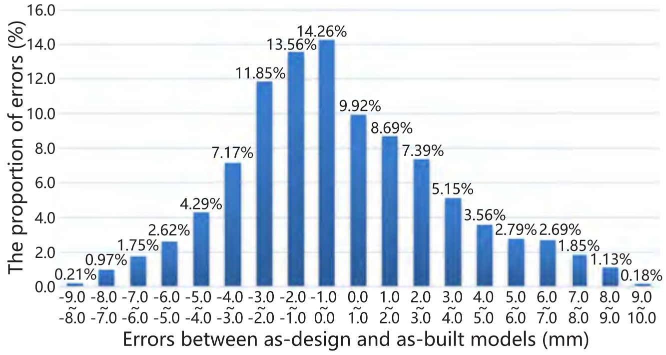

Fig. 30. The error distribution of the manual wood formwork-making method.

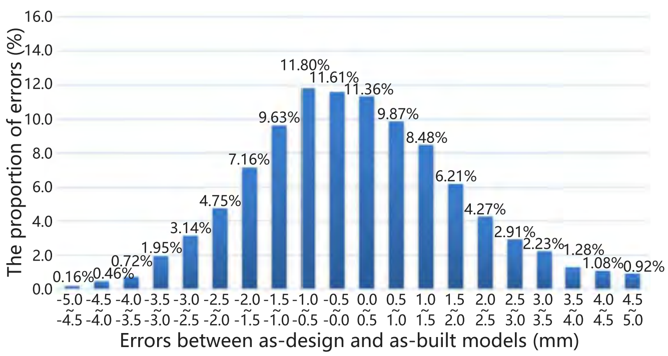

Fig. 31. The error distribution of the CNC foam formwork-making method.

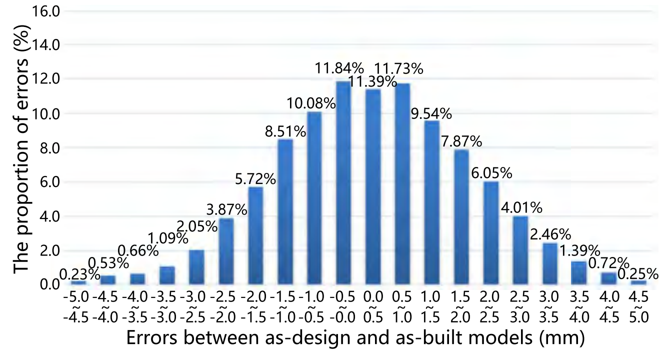

Fig. 32. The error distribution of 3D-printed formwork-making method with milling.

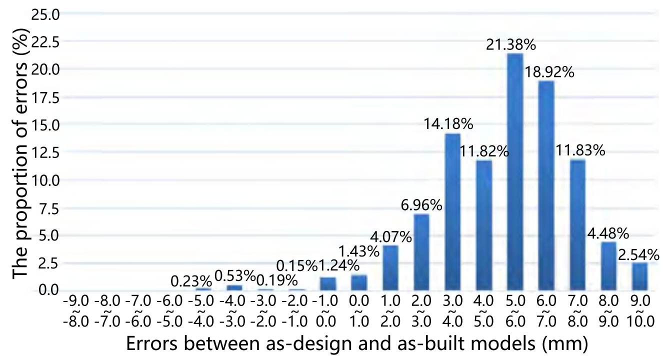

Fig. 33. The error distribution of 3D-printed formwork-making method without milling.

with similar ranges of errors and deviations. The 3D printing without milling had the highest error level and narrowed normal distribution. Table 3 lists the absolute deviations in the positive and the negative directions, the percentage of the positive and negative deviations of all compared data, and the average differences. It indicates that 3D printing with milling produced the highest accuracy with an average deviation of 1.29 mm, whereas the unmilled side had a deviation of 5.23 mm, leading us to conclude that the post-process milling significantly impacted the accuracy of 3D printing and was necessary for making the formwork. The difference value was 3.94 mm, which was very close to the 5 mm depth value of the CNC milling, thereby demonstrating that both the printing and milling steps maintained the same level of accuracy.

The CNC foam formwork had an average deviation of 1.38 mm, which was very close to the milled 3D-printed formwork. The manual wood formwork-making method produced the worst precision with an average deviation of 2.65 mm, although the average deviation was still within the permissible range of error under construction conditions. From our comparison of the making accuracy, it can be seen that the 3D printing performed best among the three formwork-making methods.

Economic Comparison

The total cost of making the formworks for this analysis included material cost, labor cost, and machine cost. As shown in Table 4, the general costs of the manual wood and CNC foam formwork-making methods were 232.80 $\$/m^2$ and 284.34 $\$/m^2$, respectively, which were inexpensive for low repetition. The cost of the 3D-printed polymer-based formwork method, on the other hand, totaled 733.53 $\$/m^2$, almost tripling the costs when compared with the other two methods. However, the foam and wood formworks can be used for only 10–20 repetitions whereas the 3D-printed formwork can be used for over 200 repetitions (Hendrixson 2018b). In consideration of the lifespan of the formworks, the average cost of each casting for 3D printing was 3.67 $\$/m^2$, which was much lower than the 11.64 $\$/m^2$ for the manual wood formwork and the 28.43 $\$/m^2$ for the CNC foam formwork. Figs. 34 and 35 illustrate the average cost using this statistical analysis of the average cost of each pour per method, which shows that the 3D-printed formwork cost was lower when the number of repetitions of the components casting reached 21 for CNC and 61 for wood. Therefore, the need for repeatability and durability of the formworks can be met by 3D printing for the mass production of customized concrete-based components.

The construction contractors for the manual wood and CNC foam formworks for the demonstration house were from China, whereas the contractor for the 3D-printed formwork was from the United States. Since the Chinese construction market has a huge advantage in its low labor and material costs, which are beneficial for the manual wood and CNC foam methods, the US construction market could benefit more from the 3D-printing method than the Chinese market could, relative to the cost of the first two methods. In the current market, while labor costs are constantly increasing, the machine and material costs are expected to decrease with the advancement of technology and materials. Hence, the life-cycle cost of 3D-printed formworks is expected to decrease. The 3D-printing method's most significant advantage is in its repeatability and durability when compared with the manual wood and CNC foam methods for the mass production of customized prefabricated buildings.

Table 3. Making-accuracy results of different formwork-making methods

Method	Area (m^2)	Max positive error (mm)	Max negative error (mm)	Proportion of positive error (%)	Proportion of negative error (%)	Average error (mm)
Manual wood formwork	9.42	9.24	−8.33	43.32	56.68	2.65
CNC foam formwork	5.64	4.93	−4.67	48.60	51.40	1.38
3D-printed polymer-based formwork (milled)	1.67	4.62	−4.45	55.41	44.59	1.29
3D-printed polymer-based formwork (unmilled)	1.67	9.88	−2.71	97.59	2.41	5.23

Table 4. Making-cost results of the three formwork-making methods

Method	Programming cost ($/$m^2$)	Material cost ($/$m^2$)	Machine cost ($/$m^2$)	Labor cost ($/$m^2$)	General cost ($/$m^2$)	Repeat time of casting	Cost of each casting ($/$m^2$)
Manual wood formwork	0	16.99	3.50	212.31	232.80	20	11.64
CNC foam formwork	0	103.32	21.45	159.57	284.34	10	28.43
3D-printed polymer-based formwork	47.61	204.93	451.05	29.94	733.53	200	3.67

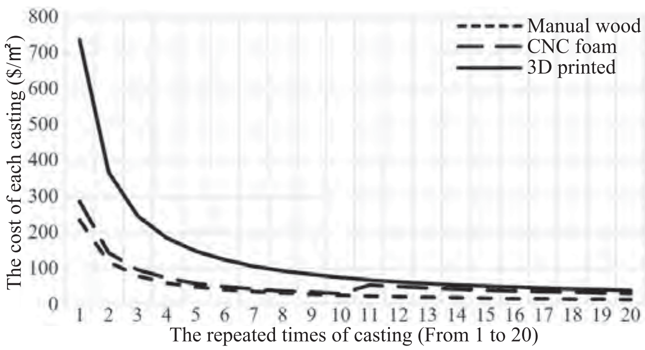

Fig. 34. The cost of each casting when the casting repetition is from 1 to 20.

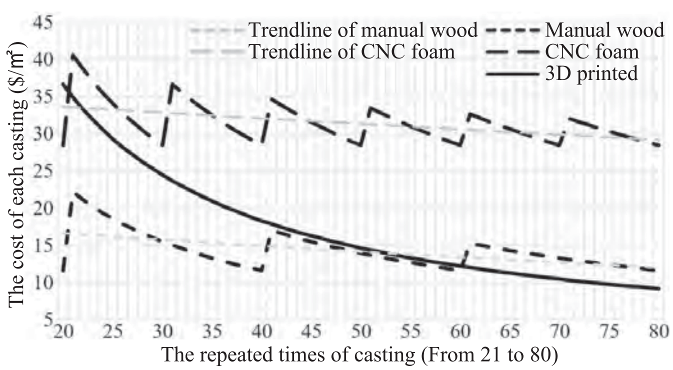

Fig. 35. The cost of each casting when the casting repetition is from 21 to 80.

Comparison of Time Consumption

As illustrated in Fig. 36, the 3D-printing method exhibited a tremendous advantage over the other two methods with respect to time consumption. Table 5 shows that the time for the 3D-printed polymer-based formwork-making method was about 1.1 h/m^2, whereas the time for the manual wood and CNC foam formwork-making methods was 9.93 h/m^2 and 14.48 h/m^2, respectively. These differences were directly related to human involvement in

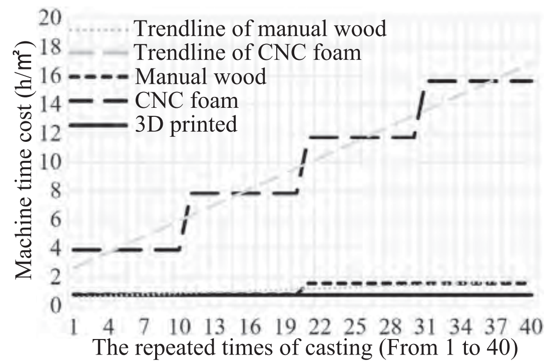

Fig. 36. The machine time cost of formwork-making.

the process. In situations in which skilled labor is not available, the 3D-printing method could be a strong solution.

From the aspect of durability when the pour repetitions are high, more foam formworks are needed than for the wood formworks. Fig. 37 indicates that when the number of concrete pours were more than 11, the manual wood method had a higher labor time cost than the CNC foam method. Fig. 38 indicates that when the number of repeated concrete pours reached 21, the manual wood method had a lower total time cost than the CNC foam method.

Optimized Design Strategy for 3D-Printed Formwork-Making

Our accuracy analysis indicated that all three formwork-making methods were within the permissible range of error to deal with highly customized or complex shapes. However, the cost and time would influence the design strategy and would lean toward using 3D printing. 3D printing is a promising method in the mass production of customized prefabricated buildings; when there are a large number of casting repetitions, it reduces lead times and labor costs and the combined composited cost of the components.

3D-printing technology can not only revolutionize the fabrication process, but can also advance the full life-cycle activities of customized buildings, especially during the architectural design process. The as-design model should be well parameterized and rationalized for the as-printed model to provide self-adaptive adjustment during the process. To fully take use of 3D printing, reducing

Table 5. Time results of the three formworks

Method	Making process	Machine time cost (h/m^2)	Number of machines	Labor time cost (h/m^2)	Number of workers	Total time cost (h/m^2)
Manual wood formwork	CNC cutting	0.785	1	0.106	1	14.480
	Fabrication	0	0	3.397	3	
	Plaster work	0	0	1.699	2	
CNC foam formwork	CNC milling	3.901	1	0.355	1	9.930
	Plaster work	0	0	2.837	2	
3D-printed polymer-based formwork	3D printing	0.486	1	0.219	1	1.102
	CNC smoothing	0.265	1	0.132	1	

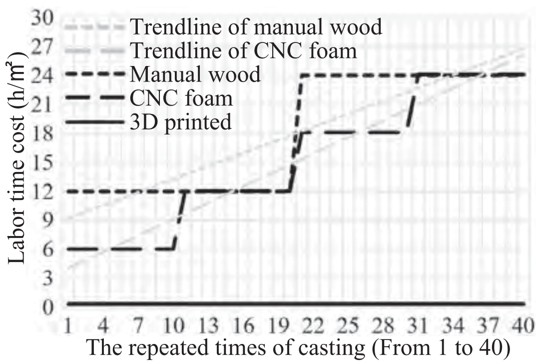

Fig. 37. The labor time cost of formwork-making.

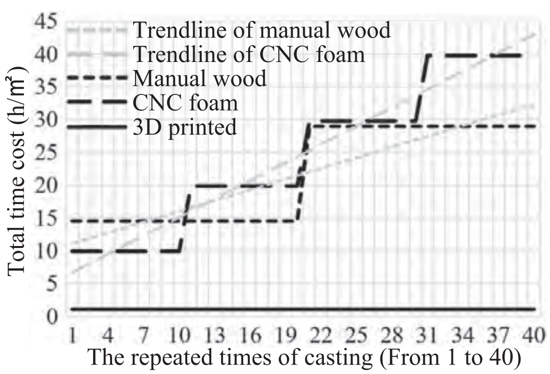

Fig. 38. The total time cost of formwork-making.

the variations of the customized components and increasing the quantity of those components would enhance the performance and efficiency of the formwork created. Meanwhile, the 3D-printed polymer-based formwork-making method needs to be supported with the simultaneous use of the foam and wood formwork-making methods for the production of lower quantity customized components in the design.

Conclusions and Future Work

This paper presents the strengths and weaknesses of the 3D-printing technology used for formwork-making through a comparison of this technology with the two conventional methods of manual wood and CNC foam. Our comparison suggests that the 3D-printed–polymer-based formwork-making method can achieve better accuracy and shorter fabrication time than the other two methods. 3D-printed formworks also show an economic advantage over the compared formwork-making methods for mass customization, especially for the prefabrication of a component with high repeatability.

The quantitative analysis and comparison presented in this paper is meaningful in demonstrating 3D printing as a superior competitive formwork-making method for customized prefabricated buildings, especially in highly repetitive settings. However, in our study, customized components were shown to have a regular hyperboloid surface with a flat curvature. Future work will therefore focus on the selection of formwork-making methods to produce concrete components with even more complex shapes, especially components with a more significant curvature or randomized patterns, because the complexity of the surface form may influence the making accuracy, time, and cost of the different formwork-making methods.

Data Availability Statement

Some or all the data, models, or code generated or used during the study presented in this paper are available in a repository or online in accordance with the funding source's data retention policies (ASTM 2010; DOE 2018; Trimble 2014). Some or all the data, models, or code used during the study were provided by third parties. Direct requests for these materials may be made to the provider as indicated in the Acknowledgments. Some or all the data, models, or code generated or used during the study are available from the corresponding author by request.

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