Robotic Pellet Extrusion: 3D Printing and Integral Computational Design

Reinforced Thin Shell System Formwork for Sandwich Concrete Walls

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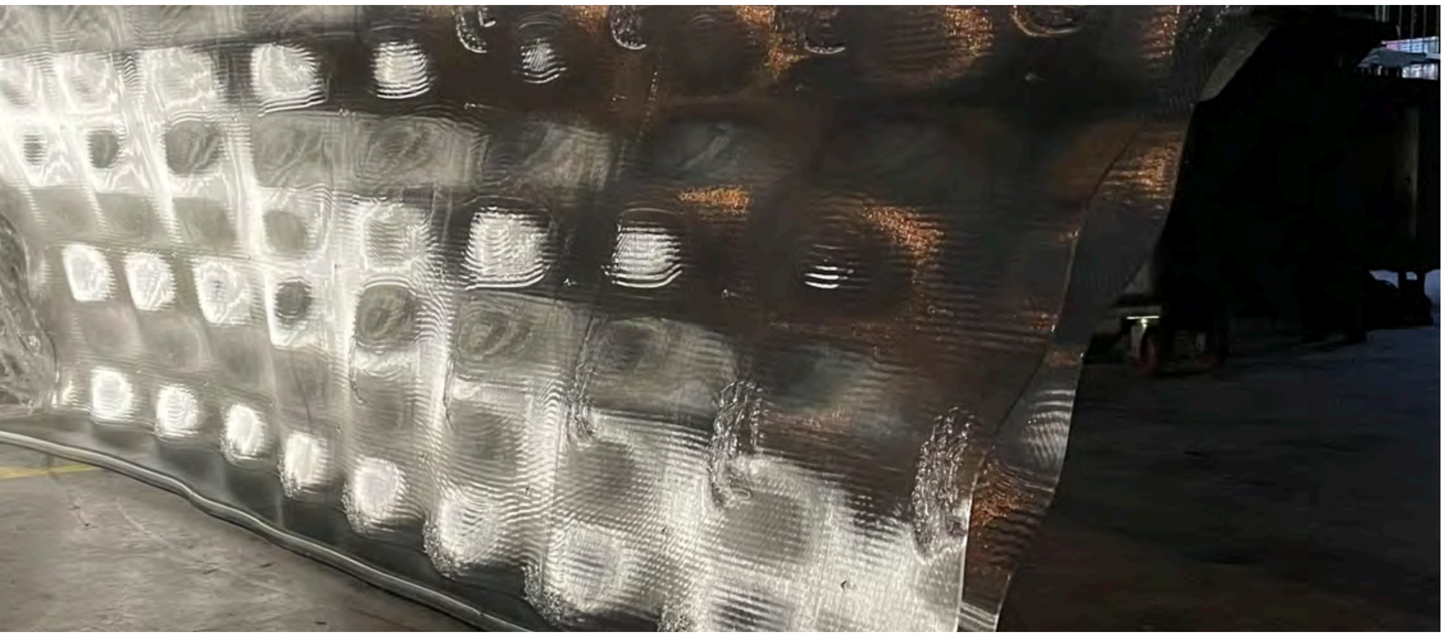


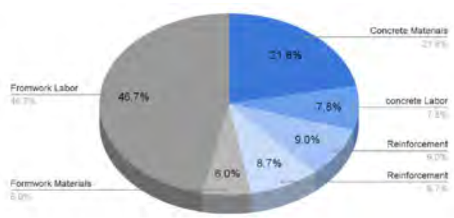
1 Full-scale 3D-printed inner core for casting insulation material entails pillow-like detailing to minimize concrete construction

ABSTRACT

Three-dimensional (3D) printing offers significant geometric freedom and allows the fabrication of integral parts. This research showcases how robotic-fused deposition modeling (FDM) enables the prefabrication of large-scale, lightweight, and ready-to-cast freeform formwork to minimize material waste, labor, and errors in the construction process while increasing the speed of production and economic viability of casting non-standard concrete elements. This is achieved through the development of a digital design-to-production workflow for concrete formwork. All functions that are needed in the final product—an integrally insulated steel-reinforced concrete wall and the process for a successful cast—are fully integrated into the formwork system. A parametric model for integrated structural ribbing is developed and verified using finite element analysis. A case study is presented which showcases the fully integrated system in the production of a 2.4m tall x 2.0m curved concrete wall. This research demonstrates the potential for large-scale additive manufacturing to enable the efficient production of non-standard concrete formwork.

INTRODUCTION

Concrete formwork plays a significant role in the cost of concrete construction, the form of a concrete structure, and the amount of concrete used in a building structure. Typically, parts designed to use minimal material entail complex geometries that require geometrically complex formwork (Aghaei Meibodi et al. 2017 and 2019). However, the construction of such formwork is usually associated with additional labor, costs, and construction waste. The cost of typical formwork amounts to anywhere from 40% to 60% of the cost of a concrete structure—exceeding the combined total cost of concrete, reinforcement materials and labor (Lab 2007). For example, cast-in-place structural concrete formwork material accounts for 6%, and formwork labor accounts for approximately 46.7% of the total cost of a concrete structure (Lab 2007) (Figure 2). The cost is even higher for irregular concrete parts with complex geometries. Thus, most concrete structures are massive, use unnecessary amounts of concrete, and are designed as rigid and orthogonal forms to serve the constraints of formwork.Compared to subtractive fabrication methods, additive manufacturing places material only where it is needed, reducing waste significantly. Our ability to digitize formwork construction and increase its fabrication freedom can significantly reduce the cost, labor, waste, and material use of concrete construction.



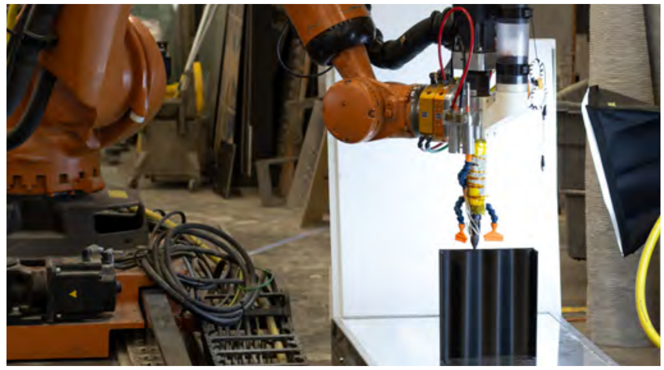
2 The schematic diagram shows the actual cost of the in-place structure. Adapted from Robert H. Lab, Jr., P.E. (Lab 2007).

Additive manufacturing technologies can open new opportunities for concrete formwork by enabling the fabrication of geometrically complex formwork economically and minimizing waste. In recent years, researchers have investigated different additive manufacturing technologies and approaches for non-standard formwork. Two technologies used for formwork production are Binder Jet and thermoplastic extrusion, which can be further characterized as fused filament fabrication (FFF) or fused granular fabrication (FGF). Binder Jet technology is used to bind sand, layer by layer, and fabricate sandstone formwork (Morel and Schwartz 2015; Aghaei Meibodi et al. 2017; Aghaei Meibodi et al. 2019; Aghaei Mebodi 2021). Binder jetting with sand offers the most significant level of geometric freedom, precision, and resolution on a large scale, but the resulting formwork is relatively heavy and fragile to handle on the construction site. Thermoplastic extrusion technology, which is of interest to this research, has been used to fabricate large-scale ultra-thin thermoplastic formwork (Peters 2014; Jipa et al. 2017; Leschok and Dillenburger 2019; Aghaei Meibodi et al. 2020; Burger et al. 2020). 3D printing of thermoplastic enables the fabrication of lightweight and recyclable formwork. The existing research has focused on 3d printing ultra-thin plastic formwork and developing concrete casting approaches that prevent the formwork from cracking under hydrostatic pressure when casting (Peters 2014; Jipa et al. 2017; Burger et al. 2020).

The common challenge in thermoplastic extrusion 3D printed plastic formwork, especially at a larger scale, is the hydrostatic pressure exerted on formwork by fluid concrete during casting. Hydrostatic pressure is the force per unit area transmitted by the freshly placed concrete perpendicular to the formwork. The hydrostatic pressure that is exerted on each point of the formwork is determined by the height and the density of the casting fluid above that point.

An approach to overcome the hydrostatic pressure has been to submerge the formwork in a bed of sand when casting the formwork (Jipa et al. 2017; Leschok and Dillenburger 2019; Aghaei Meibodi et al. 2020). Here, the sand acts to partially cancel the hydrostatic pressure from the concrete. Another approach proposed in Eggshell research has been to use a set-on-demand, accelerated concrete mix (Burger et al. 2020). In this approach, the hydrostatic pressure is reduced significantly by casting concrete in incremental volumes with an added accelerator, which causes a rapid gain in yield strength before the next batch is cast.

While these solutions to overcome hydrostatic pressure are valid, they may be challenging to scale for real-world construction. Using sand (potentially mixed with other dense materials such as calcium carbonate, bentonite, and water to form a slurry) to counter pressure hydrostatic pressure might be scalable for prefabrication but not for onsite fabrication. Even for off-site fabrication, systems must be developed to pour sand at a similar rate as casting the concrete mix; otherwise, it will break the formwork inward. In a "set-on-demand" approach, the construction process requires complex pumping and mixing equipment to proportion the accelerator. This approach also requires custom concrete mix designs that differ substantially from industry-standard self-consolidating concrete (SCC).



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METHOD

This research expands on existing research into FFF 3D printing of lightweight formwork by developing fabrication methods based on FGF (pellet extrusion) rather than FFF (filament extrusion) to speed and scale the fabrication process. It proposes to go beyond merely 3D printing ultra-thin shell formwork to 3D printing the formwork as a structurally optimized, rib-stiffened shell formwork system. The integration of reinforcement ribs into the thin shell will provide adequate strength and stiffness to retain newly cast fluid concrete in place. The integration of reinforcement ribs is not a new concept; for example, the injection-molded ABS formwork of Peri (Peri, n.d.) entails a waffle-like grid of ribs to overcome the hydro-static pressure during the casting process. Nevertheless, this research will not develop a standard and repetitive waffle-like rib system but a customized, structurally opti-mized reinforcement system that minimizes the formwork system's material usage by printing support material based on the local hydrostatic pressure in the mold.

Robotic FGF 3D Printing for Integrative Formwork

FGF 3D printing via extrusion is limited by several factors, such as the maximum material deposition rate, the maximum machine feed rate along the toolpath, and the maximum cooling rate of the deposited material, which further relates to geometric constraints. The maximum material deposition rate is controlled by factors such as the maximum melting rate of the polymer as well as process-specific factors such as the maximum force which can be applied to the filament (in the case of filament extrusion systems) or the maximum die pressure, which can be achieved (in the case of pellet extrusion systems). FFF printing with nozzle diameter less than 1mm is limited to a theoretical maximum build rate of 180cc/hr, which would translate to approximately 0.2kg/hr with PETG (Go et al. 2017). Commercially available pellet extrusion systems with nozzle diameter >1mm are available with build rates of more than 30kg/hr. The existing experimentation shows that pellet extrusion can be faster than filament extrusion for larger objects. This research utilizes a pellet extrusion system using a 3mm nozzle diameter that can print approximately 5kg of material per hour. At the component scales investigated in this research, the material extrusion rate is rarely the limiting factor. FGF 3D printing via extrusion also imposes constraints on the geometry of printed components, particularly related to unsupported overhangs. In particular, the ability to cantilever the toolpath proves to be heavily dependent on the print bead width and print speed parameters. The cooling behavior of the specific polymer used also has a significant effect on the ability to cantilever. Through prototyping, we identified the geometric limitations of the FGF and printing setup. For the optimum print speed of 0.1m/s with a bead width of 5mm and thickness 1mm, we could achieve a maximum cantilevering angle of 35°. The cantilever constraint was further integrated into the computational design method to ensure the generation of printable forms.

Concept of Integrative Formwork System for Concrete Sandwich Wall

The geometric complexity offered by 3D printing can be leveraged to design and fabricate complex formwork systems with multiple cavities and precise detailing. In this research, a formwork system with three cavities for three layers of material is developed—one cavity is for casting insulation material (the central cavity) and two outer cavities for casting concrete. The integrated reinforcement fins that help resist hydrostatic pressure and the detailing for rebar installation are printed simultaneously to the casting surface (Figure 4). The integral insulation layer acts as the core of the system and allows the outer layers of concrete to be exposed. The formwork system was designed to allow for rapid installation of the insulation and rebar before casting. Such a formwork system allows the fabrication of an insulated cast-in-place concrete wall in a single pour. It increases precision, reduces waste and material consumption in construction.

3 Robotic 3D printing setup and in-house designed and built extrusion system for printing PETG thermoplastic pellets.

4 The integrative formwork system comprises six layers of 3D printed vertical surfaces that define three cavities, two layers of the structural-reinforcement systems, and the detailing for installing the wythe ties and detailing that holds rebars in place.

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Integral Computational Design of Structurally Informed 3D-Printed Formwork

This research expands on the existing research into 3D printing thermoplastic concrete formwork by integrating fins as structural support into the formwork design and printing them as an integral part of the thin-shell formwork to withstand hydrostatic pressure without deformation. A computational design approach was developed to minimize formwork waste, which generates and sizes structural supports only where they are needed. This approach utilizes structural finite element analysis (FEA) to the computational design model that generated the formwork and its details. Thus, generating formwork variations with minimal material usage at the allowable deflection. Another set of feedback loops between prototyping and computational design models was created to identify the most efficient geometries for providing stiffness while minimizing thermoplastic and material used in 3D printing the concrete formwork.

Parametric Model of the Formwork

The developed computational design procedure optimizes the formwork's geometry in response to hydrostatic pressure and deformation. Here, a parametric model of the overall formwork system was linked to a structural analysis solver, which measures the deflection of the formwork under load. The data from the structural analysis was directly fed back into the algorithm that generates the fins.

The algorithm began with the input of a NURBS surface representing the desired form of the concrete wall element (Figure 5). This input NURBS surface was subdivided into adjoining vertical surfaces—each discretized surface is continuous from the base to the top of the formwork—to generate vertical fins tangent to the outer formwork elements. Each subsurface represents the tributary area of one load-bearing formwork element to which we refer as a fin. The fins act as a beam transferring the load of the liquid concrete (hydrostatic pressure) to the formwork base.

The width and depth of each fin element was controlled parametrically and was limited by the deflection of the thermoplastic formwork at the casting surface (Figure 6). FEA was used to determine the deflection value under hydrostatic pressure, and the results were fed to an algorithm that generated each fin's width and depth. When calculated across the length of the fin, the resulting geometry is a tapered triangular prism with the most profound cross-sectional depth occurring at the lowest part of the formwork.

Maximum Fin Width Calculation

The maximum fin width was calculated using the following equation, which assumed a uniform distributed load case on a simply-supported beam (Figure 7).

$$L = \sqrt[4]{384 E_I \delta max / 5\varpi}$$

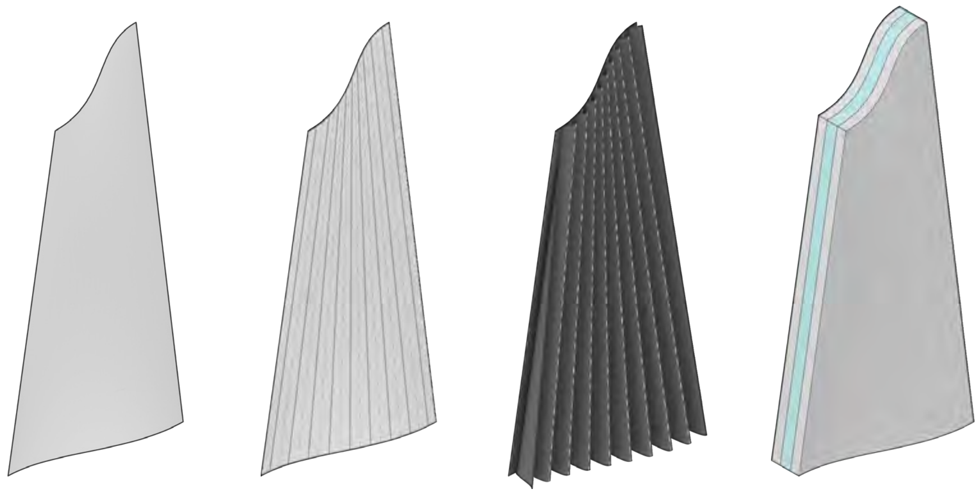
where,

L = maximum fin width *(m)*
δ_{max} = maximum acceptable deflection along fin width *(m)*
ϖ = uniform distributed load, as determined by hydrostatic pressure *(N/m)*
E_I = Young's modulus of thermoplastic material parallel to toolpath direction. *(Pa)*
I = area moment of inertia of thermoplastic cross-section *(m^4)*

Once the maximum fin width had been identified, the measurement was input as a parameter into the generative algorithm, and the surface was subdivided into individual fins. The newly generated fin surfaces were analyzed using FEA, as described in the following section.

Tapered Fin Deflection Analysis Using FEA

To address the complexity of variable loading and cross-section geometry along the length of each fin, FEA was used to determine an acceptable depth profile for each fin. The analysis was performed using Karamba3D for Grasshopper (Preisinger 2013, 2021; Rutten 2021). The following parameters were necessary for creating the FEA model: 1) fin span and cross-sections, 2) fin supports at



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5 Diagram of the generative design process: (Left to right): 1) Input NURBS surface; 2) surface subdivision; 3) fin sizing and surface loft; 4) resulting concrete cast

6 Cross-section profile of a fin element; fins are tangent to the casting surface with parametric depth and width

7 Diagram of a simply-supported beam used to define the maximum fin width

8 Diagram of the beam under hydrostatic pressure with one fixed support and two roller supports

9 Diagram of the same beam, but with rationalized loading for FEA model simulation

the top and bottom of each fin, 3) loading from hydrostatic pressure, 4) material properties of the orthotropic thermoplastic 3D print. The FEA model was then used to measure deflection along the length of each fin and optimize the tapered fin cross-section to minimize the amount of thermoplastic used while maintaining an acceptable deflection value.

Fin Span and Cross Section: the deflection of each fin was simulated using the vertical centerline of the fin surface. This curve was divided into 20 equal beam segments, with each segment having a different cross-sectional depth. The depth of each triangular cross-section was assigned by dividing the values between the base and upper section depth parameters across the length of the fin. This method rationalized the linear taper of the fin design into a stepped beam of similar performance for the sake of processing time.

The user assigns the input parameters representing the upper and lower section depths. The width of each triangular section is determined by the maximum fin width calculation. In this case study, the cross-section profile was given a thickness of 5 mm - the wall thickness of the thermoplastic print.

Supports / Load Transfer: the loads carried by the formwork are transferred to a support at the top, middle, and base of each fin. The base support was modeled as a simple fixed support and the top and middle supports were modeled as roller supports (Figure 8&9).

Loading: hydrostatic pressure was the predominant load simulated in the FEA algorithm. In a wall condition, the gravity loading was negligible and was not included in the FEA analysis. The hydrostatic pressure was calculated and applied individually for each of the 20 beam segments along the length of the fin. The following equation was used to calculate the hydrostatic pressure:

$$p = \rho g h$$

where,

p = pressure (N/m^2)
ρ = density of concrete (kg/m^3)
g = acceleration of gravity (m/s^2)
h = vertical distance between top of fin and midpoint of beam segment (m)

The resulting values were multiplied by the fin width, and the uniform linear loads were applied to their corresponding beam segments. As previously mentioned, this rationalization of the beam loading (Figures 8, 9) was carried out in order to reduce the processing time for simulating using the FEA model.

Material Properties of Orthotropic Thermoplastic 3D Print

In order to accurately simulate the deflection of the formwork in the FEA model, mechanical testing was performed on printed material specimens. The material properties were measured in accordance with the ASTM standard, D638, Standard Test Method for Tensile Properties of Plastics (ASTM International 2014). The outer formwork is printed using a short fiber (<1mm) carbon fiber reinforced PETG. This material provides for both increased mechanical properties in the printed part and faster print speeds due to a faster transition from the molten state to the rigid state. The stiffness and yield strength of the carbon/PETG is highly anisotropic due to preferential fiber alignment in the extrusion direction. Samples were produced with the print (extrusion) direction aligned to the tension direction, as well as with the layer (Z) direction aligned to the tension direction. The modulus of elasticity of the aligned samples averaged a fourfold increase over the nonaligned samples.

The 3D printed thermoplastic material exhibited orthotropic properties, with the Young's modulus value dependent on the orientation of each print layer relative to the loading direction, which is measured and indicated using the symbols E1 and E2. E1 represents the Young's modulus parallel to the layer direction of the 3D print, while E2 represents the Young's modulus perpendicular to the layer direction. In addition to the Young's moduli, the following were also calculated and input as parameters in the Karamba3D FEA model: Poisson's ratio (nue12), transverse shear modulus parallel to the layer direction (G31), transverse shear modulus normal to the layer direction (G32), yield strengths (fy1 & fy2). Values for the in-plane shear modulus (G12), a specific weight (gamma), and coefficients of thermal expansion (alphaT1 & alphaT2) were taken from the manufacturer's product data sheets of an equivalent carbon PETG thermoplastic product.

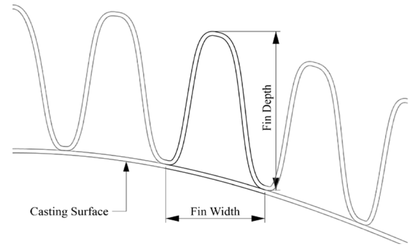
Fin Cross-section Depth Sizing

The final depth dimensions of each tapered fin were determined using an iterative process. An iterative process was used due to the loading forces on each fin being unique to its shape and orientation.The two variables (upper and lower fin depths) were input as integers ranging from 20mm to 400mm. The upper fin depth—representing the minimum fin thickness—remains static, while the lower fin depth is increased from the 20mm until the simulated fin deflection value is below the acceptable deflection value. This process is repeated for each fin, resulting in a series of fin geometries optimized for minimal material use, while still meeting the requirements for construction. After the optimization process is complete, the resulting geometry was contoured, and a toolpath was extracted from the algo-rithm. This toolpath was then input into SuperMatterTools and exported into KRL to be printed using the robotic pellet printing process.

Case Study

To produce cast-in-place concrete sandwich insulated walls with reusable PETG formwork, we developed an integral computational design method. The development of the formwork system involves the computational design, structural simulation, and optimization. The following goals guided the design of the prototype:

1. Structural deformation of the 3D printed formwork under its own dead load and while casting; integration of steel reinforcement
2. Minimizing concrete consumption



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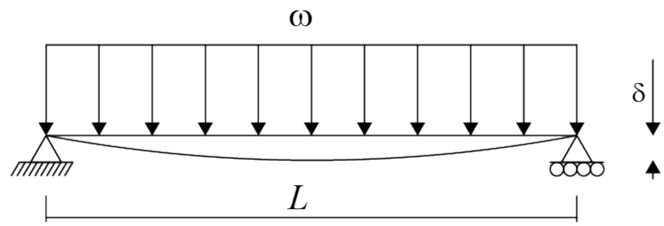

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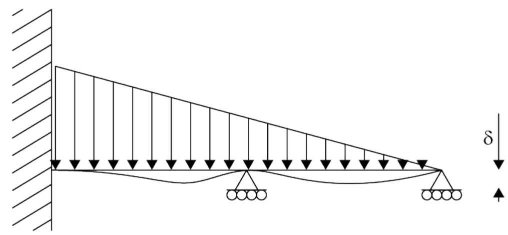

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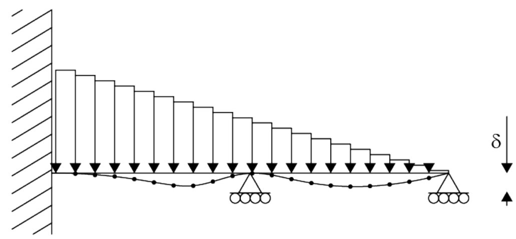

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3. Minimizing formwork material usage
4. Easy on-site assembly and formwork removal processes
5. Improving the thermal performance of non-planar concrete walls

Integrative and Load Bearing Formwork Assemblage

The developed cast-in-place formwork system for concrete sandwich insulated wall comprises several parts: removable outer formworks, an insulated core element, rebar reinforcement, and wythe ties. The wythe ties are waterjet cut with notches that fix the rebar elements in place for the duration of the casting process. When fully assembled, these components become the formwork for two concrete wythes (approx. 64mm in thickness) connected by FRP rods that penetrate through the insulative core. The overall finished wall is 200mm in depth.

The Outer Layers of the Formwork Assemblage

The outer parts of the formwork system play two major roles: resist hydrostatic pressure of the concrete mix during pouring and produce the surface finish of the

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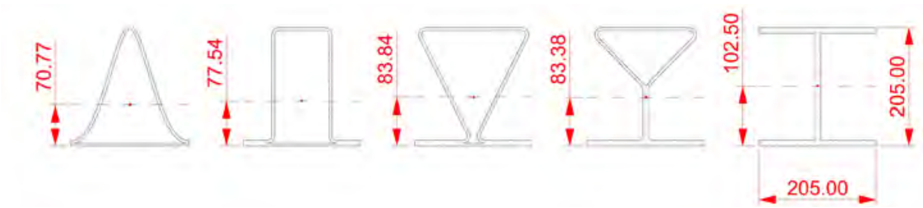

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10 3D-printed tapered fin element: (left) view from the top; (right) view from the bottom

11 Cross-section profile analysis for fin design

12 3D-printed PETG prototypes: (left) untreated casting surface; (right) filled polyester resin coated casting surface

13 Parameter study of fin layout

14-15 Deflection scale x30 for clarity

concrete cast. These parts are robotically 3D-printed, using a pellet extruder with carbon fiber reinforced PETG. Hydrostatic pressure is addressed through a fin-based reinforcement system that is integrated into the thin shell of the 3D-printed formwork. Each fin follows the surface curvature of the casting surface while spanning from top to bottom, thus transferring the load of the hydrostatic and gravity forces to the ground. The vertical edges also pick up additional loads through a CNC-milled plywood profile at the two ends of the formwork, secured to the ground plane with fasteners and adhesive.

Several iterations of formwork reinforcement systems were considered throughout the research. Iterations explored different shape profiles, spacing, depth, and orientations of the fins (Figures 11 & 13). A triangular profile provided geometrical stiffness using a minimal amount of material. Each fin consists of a triangular profile, which is smoothed into a continuous NURBS curve for increased accuracy and speed in the 3D printing process. While the extrusion system in use is positionally synchronized with the robot motion, smoothing the toolpath allows the robot to maintain a smoother velocity profile and, therefore, a more consistent bead width. This effect of smoothing on path accuracy is a complex, non-linear problem, but for formwork applications, surface finish is of high importance and this is improved by smoothing. Additionally, the fin profile tapers corresponding to the reduction in hydrostatic pressure from the bottom to the top of the formwork.

When left untreated, the surface of the 3D-printed carbon-reinforced PETG formwork is rough with small ridges forming at each layer of the printed toolpath at approximately 1mm spacing. A surface finish test was conducted comparing untreated casting surfaces, sanded/polished casting surfaces, and polyester resin-treated casting surfaces (Figure 12). Surface prototypes were waxed prior to casting and removed after 48 hours. The untreated surface required significant force to remove, while the sanded surface (although smooth to the touch) left a visual indication of the toolpath layers. The polyester-coated finish resulted in a smooth finish that required the least amount of force to remove. Coating the mold surface has clear benefits for the reusability of the mold, but potential drawbacks affecting the recyclability of the formwork.

The Internal Insulative Core

The internal core was designed to serve two purposes. First, it provides an insulative thermal break in the interior of the concrete wall, and secondly, it supports the rebar reinforcement during the casting process (Figure 16).

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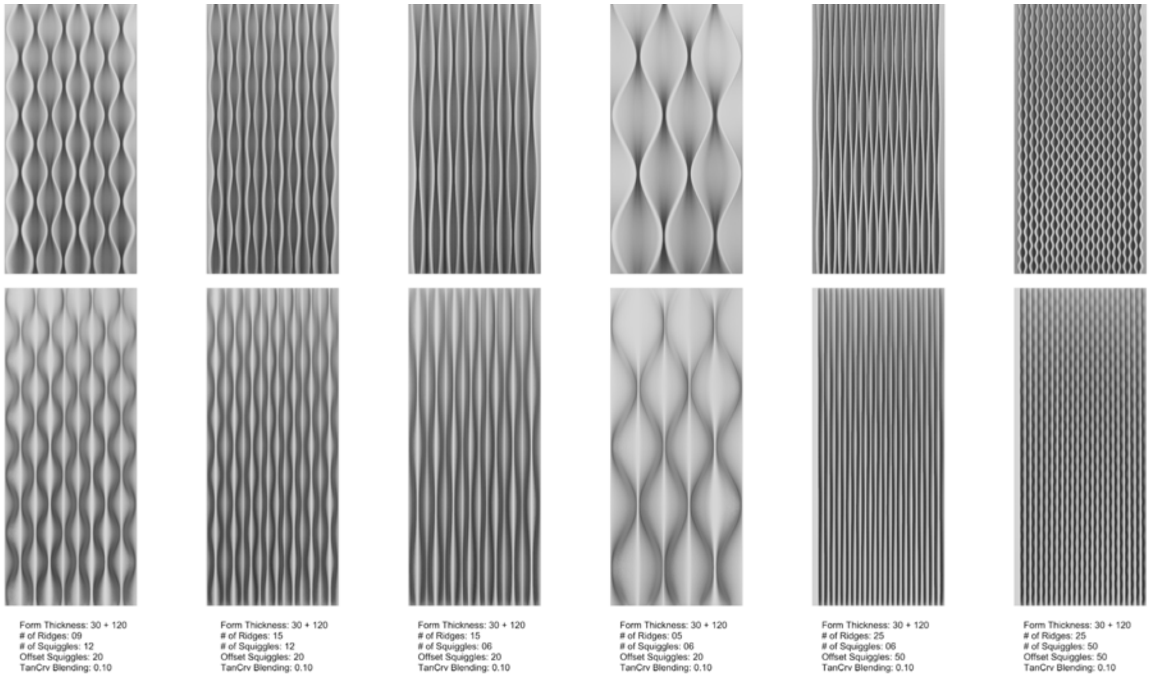

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The parametric design of the core system was developed in a way to increase the insulative performance and reduce the volume of concrete in the concrete wall. The overall geometry of the core follows the form of the wall and suspends a lattice of rebar approximately 25mm from the exterior casting surfaces. A grid of pillow-like forms in the core system protrude between individual cells of the rebar lattice, displacing the concrete mixture while still maintaining the code-mandated rebar coverage for concrete structures (American Concrete Institute 2014). The resulting geometry is a waffle-like layer of polyurethane foam—varying in thickness from 50mm to 100mm—which reduces the layer of concrete by 8.8% over a traditional smooth surface insulative core. One half-inch diameter FRP wythe ties protruded 50mm from each side of the core, spaced roughly 600mm apart. The wythe ties hold together both sides of the concrete wall and resist shear. Each tie was notched to carry rebar in both the vertical and horizontal directions. The location of these wythe ties were indicated using a marker in the printed toolpath.

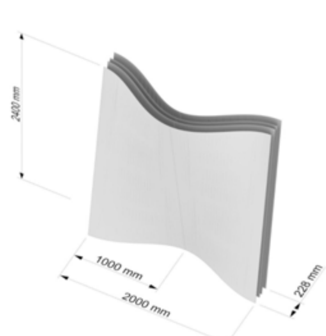
Unlike the outer formwork, this printed core element remained permanently in the wall. It was printed from standard PETG (which is more economically priced than the carbon-infused variant) and acted as a stay-in-place formwork for a polyurethane foam cast. Once the foam cured, the rebar was clipped into the FRP wythe ties and tied together with standard rebar ties. While casting concrete, this insulative core, with installed wythe ties and rebar elements, was attached to the ground plane with adhesive and secured with form ties from above to prevent floating or shifting during the concrete pouring process.

RESULTS

For this case study, a 2.4m tall x 2.0m wide lofted, freeform NURBS surface was input (Figure 14). The formwork solution needed to resist up to 49.4kN/m2 of hydrostatic pressure, with a maximum allowable deflection value of 3mm along with the height of the formwork and 1mm across the width of each fin.

The calculated maximum fin width span value of 117mm, results in 18 fins on each side of the wall formwork. Due to the inputted NURBS surface being a ruled surface, all individual fins share very similar cross-sectional profiles, tapering from a 170mm deep base to a 40mm deep top profile (Figure 15).

The amount of thermoplastic material was calculated for both sides of the 2.4m x 2.0m form. With a total surface area of 9.90m^2, the casting surface accounted for 0.0495m^3 of thermoplastic material or approximately 62.8kg. The fin support structure amounted to 21.75m^2 of



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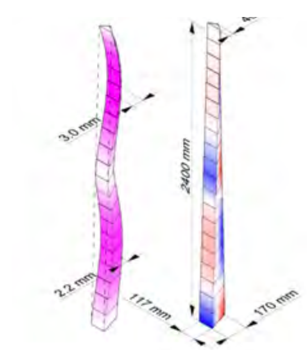

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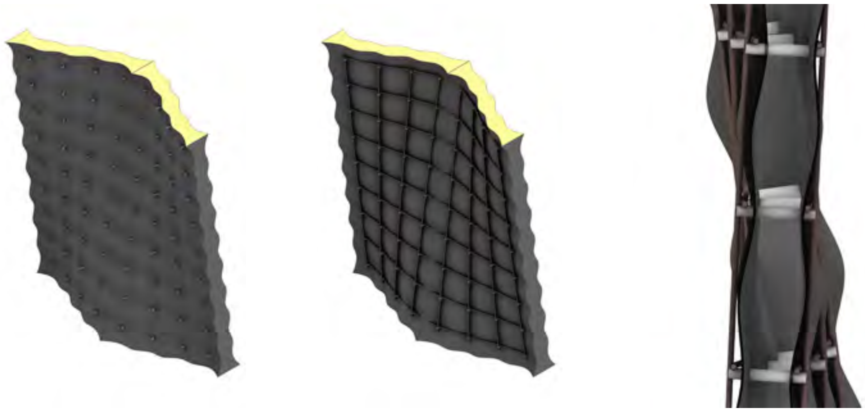

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16 Internal core formwork with pillow-like geometry as a stay in place formwork for foam (left). Notched wythe ties that hold rebars in two directions and keep the two concrete wyths together.

17 Full-scale 3D print of the inner core for casting insulation materia

18 Assembled formwork, with insulative inner core and rebar.

surface area, requiring 0.1087m^3 of thermoplastic material, or approximately 137.9kg of material. The ratio of casting surface to support material is 1:2.2. The overall outer formwork requires approximately 200.7kg of carbon PETG thermoplastic material.

Robotic FGF 3D printing using allowed for assembly of an integrative, ready-to-cast formwork with insulation and steel reinforcement (Figure 18). While the resulting formwork appears to satisfy the requirements for successful casting at construction scales, several challenges related to large-scale pellet extrusion remain. Due to the large aspect ratio (height vs. depth) of the prints, stability of the part during printing is a challenge. In the case of the external walls of the formwork, the addition of the stiffening ribs designed to overcome hydrostatic pressure assists with stability during printing. However, in the insulative cavity, which has no ribbing, the lack of support while printing led to issues with warping and part removal from the heated bed. Future work will explore the addition of internal ribs to help stabilize this component. Another known challenge is the ability to print complex geometries at high speeds. While pellet extruders are capable of high-speed extrusion, the motion control platform, in this case, a seven-axis industrial robot, is limited in its ability to maintain high speeds around sharp corners. In general, cooling of the part during printing is an ongoing challenge that limits both the maximum printing speed (as it sets a "minimum" layer-to-layer time) and causes issues with accuracy due to asymmetric cooling and warping. While smaller-scale printers address this via heated build chambers, this is challenging to deploy at the volumes required by full-scale construction molds.

CONCLUSION

The result is a novel, digital design-to-fabrication workflow for producing freeform formwork that allows cast-in-place, thermally-insulated concrete sandwich panel walls. The integration of computational design and structural optimization combined with 3D printing provides the potential to rethink concrete formwork systems. Designing and building a structurally optimized, rib-stiffened shell formwork will allow the fabrication of non-uniform concrete forms economically and with minimal material waste. The integration of assembly details and supports further reduces the labor required to assemble the molds and place steel reinforcement. Future research is planned to determine the overall geometric limitations of the process, as well as to further optimize the overall design-to-fabrication workflow.

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IMAGE CREDITS

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