

Additive Thermoplastic Formwork for Freeform Concrete Columns

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ABSTRACT

The degree of geometric complexity a concrete element can assume is directly linked to our ability to fabricate its formwork. Additive manufacturing allows fabrication of freeform formwork and expands the design possibilities for concrete elements. In particular, fused deposition modeling (FDM) 3D printing of thermoplastic is a useful method of formwork fabrication due to the lightweight properties of the resulting formwork and the accessibility of FDM 3D printing technology. The research in this area is in early stages of development, including several existing efforts examining the 3D printing of a single material for formwork—including two medium-scale projects using PLA and PVA. However, the performance of 3D printed formwork and its geometric complexity varies, depending on the material used for 3D printing the formwork. To expand the existing research, this paper reviews the opportunities and challenges of using 3D printed thermoplastic formwork for fabricating custom concrete elements using multiple thermoplastic materials.

This research cross-references and investigates PLA, PVA, PETG, and the combination of PLA-PVA as formwork material, through the design and fabrication of nonstandard structural concrete columns. The formwork was produced using robotic pellet extrusion and filament-based 3D printing. A series of case studies showcase the increased geometric freedom achievable in formwork when 3D printing with multiple materials. They investigate the potential variations in fabrication methods and their print characteristics when using different 3D printing technologies and printing materials. Additionally, the research compares speed, cost, geometric freedom, and surface resolution.

- 1 PLA thermoplastic formwork fabricated with FDM 3D printing.

INTRODUCTION

Concrete is the second most used material in the world, preceded only by drinking water, and is responsible for 8% of the world's carbon emissions. According to material chemist Karen Scrivener, the high consumption of concrete results from the fact that it is a very "low impact material" and replacing it with another material would ultimately increase the carbon footprint of the structure (Crow 2008, 63). In construction, concrete is a versatile and ubiquitous building material with structural integrity and the convenient ability to assume any shape and surface detailing. Yet the architectural potential of a concrete element is largely limited by our ability to fabricate its formwork.

Traditional methods used in formwork production are geometrically constraining, labor-intensive, and materially expensive. In fact, the cost of formwork can amount from 40% to 60% of the overall construction cost of a building, exceeding the combined total cost of concrete mixture, reinforcement materials, and labor (Lab 2007).

Additive manufacturing of formwork has expanded the geometric vocabulary of concrete design and enabled several new approaches to the manufacturing of concrete formwork. For example, binder jet 3D printing (BJP) was used in the production of a lightweight concrete slab in *Smart Slab* (Aghaei Meibodi et al. 2018), a concrete truss (Morel 2014), and the sprayed thin shell of the Swiss Pavilion at the Venice Biennale (Dillenburger 2016). While the BJP method offers a high level of geometric freedom, detailed resolution, and geometric precision of fabricated parts when compared to other 3D printing techniques, our research explores alternative methods of fabrication—using fused deposition modeling (FDM) technology—to fabricate thermoplastic formwork.

Compared to BJP, FDM 3D printing is widely accessible, can be used at a variety of scales, requires less postprocessing, uses less expensive printing materials, and requires less energy. The thermoplastic formwork manufactured using FDM is also lightweight, easy to transport, recyclable, reusable, and removable. For these reasons, FDM 3D printing of concrete formwork shows significant potential for its use in the construction industry.

There are several examples of research showcasing the benefits of FDM applications in concrete formwork; Peters (2015) presented small-scale flexible formwork based on FDM technology, Gardiner, Janssen, and Kirchner (2016) presented 3D printed wax formwork, thin-shell PLA formwork was used for a concrete canoe (Jipa et al. 2019), and dissolvable PVA was applied in a 900 mm high capital

formwork (Leschok and Dillenburger 2019) and a 115 mm scaled-down column (Doyle and Hunt 2019). The body of research exploring adaptations of FDM in large-scale concrete construction is at an early stage of development, and the existing efforts are limited to the additive manufacturing of a single-material formwork—namely PLA, wax, and two medium-scale projects in PVA.

Employment of any technology for construction should allow fabrication of large-scale formwork in a timely and economical manner. Adapting FDM 3D printing methods, which have primarily been used for small-scale prototypical parts, to meet the scale and criteria of architectural construction introduces many challenges:

- FDM is a relatively slow 3D printing process, and speeding up the printing time has a negative impact on the precision and resolution of printed parts. Printing speed varies largely depending on the printing material, technique (robotic vs. desktop printer), and the geometry being printed (for example, branching geometries would require multiple start and stop points throughout the printing process).
- Conventional 3D printing of certain geometric features, such as overhangs and cantilevers, requires auxiliary support structures that significantly increase the fabrication time and the material waste when fabricating formwork with complex geometries.
- The interface between 3D printed layers is prone to delamination due to hydrostatic pressure of concrete against the formwork.
- Formwork removal is challenging for complex geometries with undercuts and small pockets. Care must be taken to ensure proper formwork draft angles and eliminate chipping on the concrete surface.
- Unavailability of design tools that enable precast and its formwork design with respect to the fabrication constraints of FDM 3D printing.

METHOD

This research project expands on the existing field of FDM 3D printed concrete formwork by investigating the degree of geometric freedom achievable in concrete formwork when printing with different materials—namely PLA, PVA, and PETG—and different FDM printing techniques—namely robotic pellet extrusion and filament-based Cartesian machines.



2 Robotic arm fitted with a custom-fabricated pellet extrusion end-effector.

PLA, PVA, PETG, and Multimaterial

This research seeks to achieve formal complexity in concrete by cross-referencing and investigating PLA, PVA, and PETG print materials, as well as a combination of PLA-PVA formwork. PLA (polylactic acid) is a common plastic material in the 3D printing industry, being both biodegradable and produced from renewable organic starches (Grossman and Nwabunma 2011). PVA (polyvinyl acetate) is a water-soluble synthetic polymer often used for support material on complex 3D prints due to its ease of removal when in direct contact with water. This research uses PVA to directly 3D print the formwork parts. Due to its high sensitivity to moisture, PVA requires airtight storage containers, and because of the material's sensitivity, PLA can clog the nozzle if it is left slightly hot or cold when not extruding. PETG (polyethylene terephthalate glycol) is a thermoplastic copolyester with high chemical resistance, durability, and ductility. It is also fully recyclable. This research hypothesizes that combinatory additive manufacturing of multimaterial formwork as a new approach will expand the geometric freedom of formwork in an economical manner.

Pellet Extrusion vs. Filament-Based Extrusion

Pellet-based and filament-based extrusion methods of 3D printing are both valid approaches to geometric complexity and are examined against each other in this research. In filament-based extrusion, thermoplastic filament is fed through a geared extruder that pushes it into a heat block, which melts and extrudes the polymer through a nozzle. In pellet-based extrusion, granules of material are fed

through a hopper into a barrel with multiple heat zones. A motor-driven screw pushes the molten plastic through the barrel and out of a nozzle. Pellet-based extrusion has the following advantages over filament-based extrusion in the context of large-scale production in construction:

- Pellets come in a much greater variety of material choices. There are many pellets with high levels of carbon fiber that could not be produced in the form of filament, as it would be too brittle to wind onto a spool.
- Pellets can cost up to 10 times less than their filament counterparts.
- Pellet extruders can extrude significantly faster than filament-based extruders, since the pellet extruder's flow rate is only limited by the size and speed of the screw inside the barrel. In filament-based extrusion, flow rate is limited to speed of the filament drive wheel and the diameter of the nozzle, which must be smaller than the diameter of the filament to maintain the pressure and melt consistency needed for a quality print.
- Two advantages of pellets are the portability of the material and the ability to continuously dry and load the material into the end effector. When printing a 30 kg part with filament, the spool containing the filament would need to be replaced up to seven times.

Robotic vs. Desktop Printer

In this research, pellet extrusion was investigated using a six-axis robotic arm fitted with a custom-built pellet extruder end effector (Fig. 2). The pellet extruder was fitted with a 2 mm diameter print nozzle and integrated air

cooling. The filament-based extrusion was explored using a large-format 3D printer with a build volume of 305 × 305 × 605 mm and a three-axis Cartesian system featuring a 0.4 mm diameter nozzle.

Computational Design

A synergy between FDM 3D printing of formwork and computational design is important in order to fully utilize the geometric freedom offered with 3D printing, achieve a high degree of customization, materialize the geometric complexity offered by algorithmic design, and reveal a new set of formal and topological possibilities.

In this research, computational design, material, and fabrication experiments are synchronized to create a feedback loop between them. Because of the flexibility offered by algorithmic and computational design, the design can be constantly reformed by feedback received from material and fabrication experiments.

CASE STUDY

To examine these approaches against the contextual requirements of architecture and construction—scale, production speed, cost, and structural performance—three concrete columns were designed and fabricated with identical bounding dimensions (1.00 m height × 0.35 m diameter), and a framework was developed for the exploring different methods.

The column is an ideal building element to express the geometric freedom offered by computational design and additive manufacturing. While the primary function of columns is to transfer the structural loads of a building,

they also contribute to the aesthetic look of a building and their evolution expresses the technological capability of their time. Three case studies showcase the potential of FDM 3D printing for freeform formwork, with a variety of materials, to exceed what is possible through conventional formwork making methods.

FDM Printing of PLA and Agent-Based Computing of Slender Load-Bearing Ribs

The first column expands upon existing research into ultrathin-shell concrete formwork by increasing the dimensions of the 3D printed formwork, examining its ability to resist hydrostatic pressure, casting slender concrete elements of varying diameters (10–50 mm), and enabling geometric and functional complexity. The 1 m tall, ultrathin 3D printed formwork—with a wall thickness of only 0.8 mm—was printed in 122 hours and used only 1.42 kg of PLA filament (Figs. 3, 4).

The computational design framework of this column was developed on the logic of swarm intelligence (Bonabeau, Theraulaz, and Dorigo 1999) and was employed using multiagent algorithms (Snooks 2018 and 2020). In a swarm-intelligent system, complex collective behavior emerges from interactions among individuals that exhibit simple behavior (Bonabeau, Theraulaz, and Dorigo 1999). Here, the design solution space is not predefined but emerges as a result of the interactions among and between individuals and their environment, as much as from the behaviors of the individuals themselves.

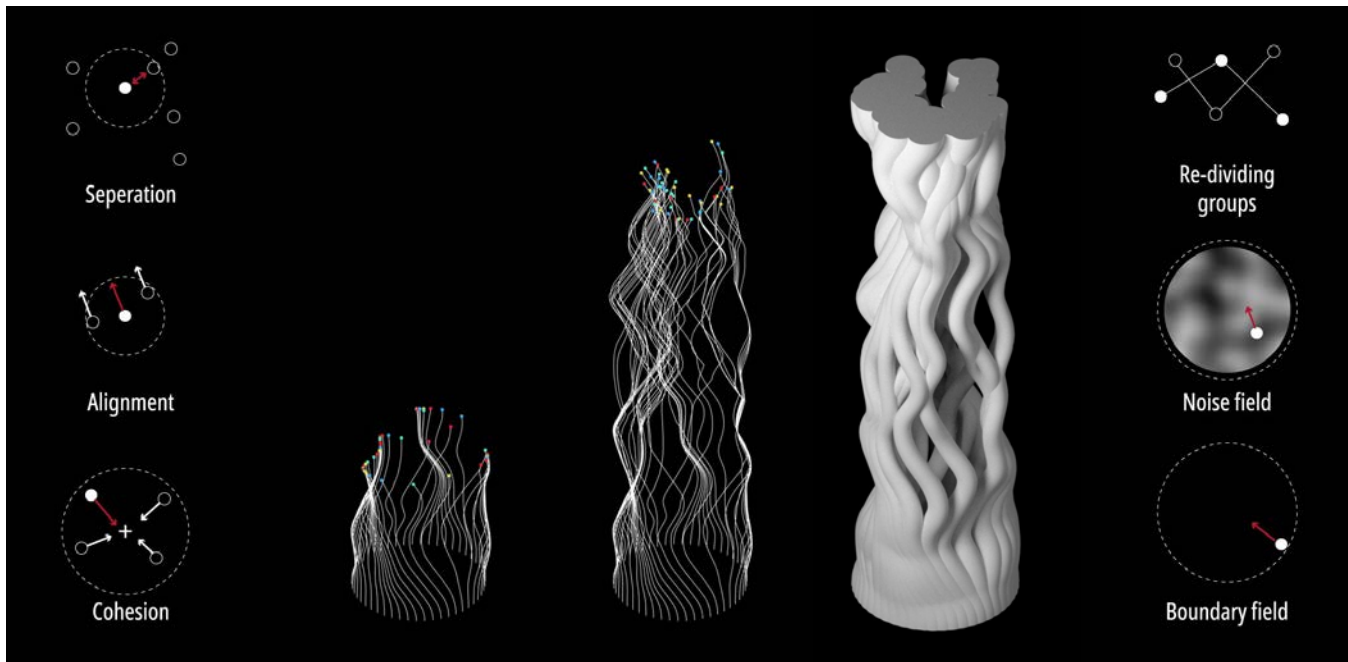
In this case study, a multiagent based algorithm was developed to connect the concrete rheology, structural



3 Ultrathin 3D printed PLA formwork with a 0.8 mm wall thickness.



4 Detail of the layer resolution used for ultrathin 3D printed PLA formwork.



5 Visualization of the agent-based computational design process.

stability under dead load, material reduction, ornamentation, and castability. The geometry of the column emerges from the paths generated as a result of the interaction between agents representing the gravitational flow of fluid concrete (simulation of gravity forces) and their cohesion and alignment behaviors, informed by aesthetic and structural performance (Fig. 5).

This experiment opens the door to a novel hybrid design approach between the fields of agent-based design and computational fluid dynamics as they relate to the 3D printing of complex formwork. The question is: How does the method connect and enable cooperation between these various individual fields with collective performance? What interactions are needed to produce a formwork with minimal material that is stable throughout casting?

From the same model, the formwork parts and their detailing were generated automatically using the embedded fabrication logic built into an algorithm. Design model and fabrication techniques coevolve through a feedback loop between the generative design processes, refining the process of large-scale fused deposition modeling and prototypical casting. To counterbalance the hydrostatic pressure applied to the ultrathin formwork when casting, the formwork was placed into a reusable sandbox.

FDM Printing of PVA and Computing of the Inner Voids

The second column expands on existing research into water-soluble formwork by examining the performance of large-scale PVA formwork (1 m height) and strategically

combining PVA and PLA prints into a single formwork. PVA dissolves in a high-moisture environment (Fig. 6); therefore, a formwork application enabled new design features for concrete elements with complex geometry, including inner voids, undercuts, long tubular voids, and deep hollow areas. However, the print speed of PVA was limited to ensure proper layer adhesion and required careful moisture control. By combining PVA and PLA, PVA was selectively applied to locations of geometric complexity and later washed away. The remainder of the formwork was printed in PLA, where formwork removal was not a constraint.

The multimaterial formwork consists of one PVA and two



PLA parts, printed using 1.75 mm diameter filament. The PVA filament required special considerations to prevent it from reacting with the water content present in the air, thus degrading the quality of the filament by producing air pockets in the material. This issue was mitigated by providing a controlled printing environment using desiccant and an airtight enclosure to dehumidify the material sealed inside. Also, the initial PVA printing tests did not properly adhere to the printing bed. This was resolved with a textured tape placed on the bed, an increased first layer extrusion rate (150%) and a decreased print speed (35 mm/s).

Print time was a major consideration in the production of the formwork. To accelerate the printing process, the print was split into PVA and PLA material sections, because printing with PLA is faster than PVA for the same geometry. The 640 mm high PLA parts were printed in 26h20m and the 360 mm high PVA part was printed in 37h30m.

The design of the geometry evolved along with material experimentation. PVA allowed for easy removal of formwork with undercuts and pockets, while the removal of the PLA was much more challenging and cumbersome with these features. Although PVA was initially chosen for its desirable water-soluble properties to ease the formwork removal, the first test showed that the water content in the concrete mixture weakens the structural performance of the PVA formwork. The wall thickness in this early prototype consisted of 2 shells with 0.4 mm width for each shell (0.8 mm in total). Because the PVA formwork would be exposed to a much higher moisture content in the full-scale cast, an additional layer was added to the shell, making the wall 1.2 mm thick.

Robotic Pellet Extrusion of PETG Formwork with Fabrication-Informed Computational Design

The third column design explores the robotic pellet extrusion of PETG formwork and addresses the demand for self-supporting reusable formwork that can be assembled on-site and withstand the hydrostatic pressure of cast-in-place concrete construction. The resulting 1 m tall, 6 kg, clear PETG thermoplastic formwork was printed with a 1 mm layer height and 3 mm wall thickness in eight hours. The robotic printing process was developed based on the following criteria: print speed, printable volume, layer height, wall thickness, degree of overhang, and the surface resolution. These performance criteria were selected for their impact on the overall fabrication time, print quality, and degree of geometric complexity in the fabricated formwork. Several permutations of these criteria were tested through an iterative prototyping process, thus identifying the constraints of the robotic printing setup. For example, it was found that the optimal print speed, layer height, and wall thickness to be 35 mm/sec, 1 mm, and 3 mm, respectively. These constraints define an ideal set of printing standards that could be applied to the final formwork print.

The iterative prototyping process revealed specific geometric constraints related to toolpath overhang between layers. Overhangs occur when the input geometry has a surface curvature in the vertical plane (Fig. 7a). When printing at 35 mm/s with a 3 mm extrusion width and 1 mm extrusion height, tests show that this overhang value is constrained to a maximum overhang angle of 33° between layers. Any surface curvature beyond this angle will cause significant surface deformation and eventual failure in layer adhesion. This type of failure would create

- 6 PVA concrete cast prototype, before (left) and after (right) formwork removal.
- 7 Robotic pellet extrusion case study, from left to right:
 - (a) Geometric analysis of print overhangs, as constrained by robotic pellet extrusion.
 - (b) Parametric model of the formwork.
 - (c) 3D printed PLA core (red) embedded within the transparent PETG formwork to reduce concrete use.
 - (d) PETG formwork capable of resisting the hydrostatic pressure of wet concrete without the need for additional support.



large openings in the formwork surface, leaving it unable to contain the concrete mixture.

To prevent overhang failure during the print, a Python script was developed to simulate and identify areas of the input geometry that exceed the limits of the robotic setup (Figs. 7a and 7b). Using this script, we were able to analyze and modify the surface geometry to meet the constraints prior to the actual print. Failure toward the end of a large-scale robotic print operation is both costly in terms of time and material. Thus, this fabrication-informed computational process increases the likelihood of a successful print and the efficiency of the printing process.

Once printing was completed, and the formwork panels were assembled, the formwork was prepared for concrete casting (Fig. 7c). A PVA-based mold release was painted onto the casting surfaces and silicone sealant was applied to the seam between each panel. A 3D printed PLA core element was placed in the center of the formwork to reduce concrete use and provide a functional core within the column to allow for integrated building services, such as electrical conduct, plumbing, air ducts, etc. An ultra-high-performance, fiber-reinforced concrete mixture was poured into the cavity of the formwork (Fig. 7d), and the concrete was visually inspected for air pockets through the transparent formwork. Once cured, the formwork was unbolted and removed, and the PVA mold release was rinsed from the concrete surface.

Hydrostatic pressure is the main force that the PETG formwork must resist during the casting process. The ductile nature of PETG increases its strength, but also results in deformation under load. It was observed that a deformation of up to 10 mm could occur without stress failure in the formwork. Tests performed with base attachment methods (securing the formwork to the base) that do not allow for this lateral movement resulted in formwork cracking and concrete leakage. Thus, care must be taken to design connections that can allow sufficient deformation.

RESULTS AND DISCUSSION

The results of the research are three different approaches to the design and fabrication of 3D printed thermoplastic formwork for concrete columns (Figs. 8, 9). Each method explores the ability to FDM print large-scale formwork using a different process. The following data was documented from each process for examination and comparison: print speed, geometrical freedom, formwork strength, and formwork removal. A summary of these results is presented in Figure 10 and in the following comparisons:

1. There were large variations in print speed between the printing processes, with the robotic pellet extrusion of PETG effectively printing each layer three times faster than PVA and 27% faster than PLA. Although the actual speed of the nozzle is sometimes faster in Cartesian printing, the increased volume of material flowing through the pellet extruder saves time by producing a sufficient wall thickness without the need for multiple passes.
2. The allowable geometrical complexity is heavily dependent on the material properties of the thermoplastic and the printing process. Robotically printed PETG was unable to reach the same overhangs as seen in the Cartesian methods (33 degrees vs. 45 degrees). In contrast, PVA was ideal for complex geometric forms (including narrow pipes, undercuts, and unreachable voids) due to its water-soluble properties. The PLA prints were capable of the same level of geometric complexity as the PVA counterparts; however, consideration must be made regarding the formwork removal.
3. PVA was the weakest of the formwork materials. Its water-soluble properties left it susceptible to degradation when left in a typical construction environment, which was worsened by the addition of water from the concrete. The PLA, although stronger than PVA, still required the support of a sandbox during the concrete casting process due to its thin wall thickness (0.8 mm). The much thicker PETG formwork (3 mm) was capable of resisting the hydrostatic forces of the concrete mixture without need for a sandbox.
4. The formwork removal process was conceptually unique for each case study. The PETG formwork, with its 3 mm wall thickness, was easily removed from the cured concrete and could be reassembled and reused in other concrete pours. However, the increased layer height of the robotic printing process left a noticeable texture on the concrete that may not be desired in certain situations. The PLA formwork removal process required cutting off the PLA in small pieces, a process that is both labor-intensive and destructive to the formwork. The PVA was the easiest to remove, as it could simply be rinsed or brushed off.

None of the thermoplastic materials outperformed the others in all categories; rather, each material has its unique strengths to be applied as necessary to achieve the desired result. This is exhibited most clearly in the hybrid approach of the PVA-PLA case study (Fig. 11). The addition of PLA decreased printing times (up to 50% less) and added cost



8a



8b



8c



9

8 Three case studies of thermoplastic formwork enabled by FDM 3D printing: (a) PVA-PLA formwork for branched and twisted columns with inaccessible void in center; (b) PETG formwork produced through robotic pellet extrusion; (c) PLA formwork generated using agent-based computation print.

9 Resulting fiber-reinforced concrete columns.

Print Material	PLA	PVA	PETG
Material Format	1.75 mm filament	1.75 mm filament	Pellet
Printer Type	Enclosed Cartesian FDM printer	Enclosed Cartesian FDM printer w/ filament dry box	Pellet extruder end-effector on robotic arm
Nozzle Size (mm)	0.40	0.40	2.00
Nozzle Temp (C)	205	200	220
Print Speed (mm/s)	40.00 inner shell 70.00 outer shell	30.00	35.00
Extrusion Layer Width (mm)	0.40	0.40	3.00
Layer Height (mm)	0.25	0.40	3.00
Formwork Wall Thickness (mm)	0.80	1.13	3.00
Formwork Wall Layers	2	3	1
Effective Print Speed (Print Speed / # of Wall Layers) (mm/s)	27.50	10.00	35.00
Geometric Features (Undercuts, Inner Voids, and Narrow Long Tubes)	Branched and narrow long tubes (10–50 mm diameter), accessible for formwork removal	Branched and narrow twisted tubes (30–50 mm diameter) with unreachable voids and inner core	Freeform surface with undulating details. Inner formwork insert creates a voided core.



10

Matrix detailing the material, print setup, and formwork geometry developed through prototyping, which allows for successful 3D printing of formworks and cross-referencing between different formwork systems.

11

Intersection of PLA and PVA materials on a case study column formwork.

savings in areas where inner voids and undercuts are not present. The use of PVA shows promise in areas in which geometric complexity is present and a solution for fast and efficient formwork removal is needed.

CONCLUSION

This project demonstrates the production of lightweight concrete formwork—using PLA, PVA, and PETG—for the construction of structural concrete columns. FDM 3D printing of PLA thin-shell formwork can be used for extremely complex geometric features, including long tubular structures, but access for formwork removal should always be provided; FDM 3D printing of PVA is a great approach for higher-geometric complexity where access for formwork removal is limited. The PVA-PLA formwork can be a solution to a diversified complexity in concrete elements while keeping up with the speed and economy of production. Finally, robotic pellet extrusion of PETG is fast and efficient, and enables production of larger durable parts in a single print. In conclusion, this research shows that a hybrid and combinatorial approach to additive manufacturing can be more economical and efficient while enabling a high degree of geometric complexity.

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REFERENCES

- Aghaei Meibodi, Mania, Andrei Jipa, Rena Giesecke, Demetris Shammas, Mathias Bernhard, Matthias Leschok, Konrad Graser, et al. 2018. "Smart Slab." In *ACADIA 2018: Recalibration: On Imprecision and Infidelity [Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, Mexico City, Mexico, 18–20 October 2018, edited by P. Anzalone, M. del Signore, and A. J. Wit, 320–327. CUMINCAD.
- Bonabeau, Erik, Guy Theraulaz, and Marco Dorigo. 1999. *Swarm Intelligence: From Natural to Artificial Systems*. Oxford: Oxford University Press.
- Crow, James Mitchell. 2008. "The Concrete Conundrum." *Chemistry World* 5 (3): 62–66.
- Dillenburger, Benjamin. 2016. "Maschinelle Übersetzungen." *Tech21* 23 (June): 24–27.
- Doyle, Shelby E., and Erin L. Hunt. 2019. "Dissolvable 3D Printed Formwork." In *ACADIA 19: Ubiquity and Autonomy [Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, Austin, TX, 21–26 October 2019, edited by K. Bieg, D. Briscoe, and C. Odom, 179–187. CUMINCAD.
- Gardiner, J. B., S. Janssen, and N. Kirchner. 2016. "A Realisation of a Construction Scale Robotic System for 3D Printing of Complex Formwork." In *33rd International Symposium on Automation and Robotics in Construction*, 515–521. Auburn: ISARC.
- Grossman, Richard F., and Domasius Nwabunma. 2011. *Poly(lactic acid): Synthesis, Structures, Properties, Processing, and Applications*. New Jersey: John Wiley & Sons.
- Jipa, Andrei, Mathias Bernhard, Nicolas Ruffray, Timothy Wangler, Robert Flatt, and Benjamin Dillenburger. 2019. "Formwork Fabrication Freedom for a Concrete Canoe." *Gestão & Tecnologia De Projetos (Design Management and Technology)* 14 (1): 25–44.
- Lab, Robert H. 2007. "Think Formwork—Reduce Costs." *Structure magazine* (April): 12–14.
- Leschok, Matthias, and Benjamin Dillenburger. 2019. "Dissolvable 3DP Formwork." In *ACADIA 19: Ubiquity and Autonomy [Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, Austin, TX, 21–26 October 2019, edited by K. Bieg, D. Briscoe, and C. Odom, 188–197. CUMINCAD.
- Morel, Philippe. 2014. "Sand Molds for Ultra-High-Performance Concrete." Architecture trade fair in FRAC Centre in Orléans.
- Peters, Brian. 2015. Formwork for Architectural Applications and Methods. US Patent 20150336297, filed May 21, 2015.
- Snooks, Roland. 2018. "Sacrificial Formation." In *Towards a Robotic Architecture*, edited by A. Wit and M. Daas, 100–113. Novato, CA: Oro Editions.
- Snooks, Roland. 2020. *Behavioral Formation: Volatile Design Processes and the Emergence of a Strange Specificity*. New York: ACTAR.

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