3D Concrete Printed Construction Systems Part 2: An Overview of 3DCP Construction Practices

Technical Findings—Final Report

U.S. Department of Housing and Urban Development | Office of Policy Development and Research

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3D CONCRETE PRINTED CONSTRUCTION SYSTEMS PART 2: AN OVERVIEW OF 3DCP CONSTRUCTION PRACTICES

TECHNICAL FINDINGS—FINAL REPORT

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Foreword

HUD has studied the diffusion of innovation in the residential building industry for decades. HUD has also encouraged innovative solutions to improve the affordability and performance of housing, with a special emphasis on low- and moderate-income families. Innovative solutions are needed to address today's housing challenges, which include a shortage of affordable housing supply, the need for resilient construction to reduce damage by natural disasters, and housing solutions for people experiencing homelessness and other at-risk populations.

Three-dimensional concrete printing (3DCP) technology is an innovative method of construction, using robotics and specially formulated concrete material to achieve greater design flexibility, faster material hardening times, and a wide range of mechanical properties without the need for conventional formwork. The technology has been in development for years in various universities, but adoption has been slow in the United States.

3DCP residential buildings have the potential to address many housing supply challenges, including the current labor shortages in the construction industry. In addition, 3DCP residential buildings are concrete structures that can resist natural hazards, such as high wind conditions and fire, so 3DCP technologies could improve resilience. In the past few years, many types of residential buildings have been constructed using 3DCP technology, from single-family homes to larger apartment buildings.

This research study, conducted for HUD's Office of Policy Development and Research by the Home Innovation Research Lab, draws on interviews of home builders and contractors, visits to job sites, and a national survey of 305 homebuilders to understand challenges and opportunities in accelerating the adoption of 3DCP technology in residential buildings.

The two-part primer provides (1) an overview of the market potential for 3DCP technology and (2) an introduction to 3DCP construction practices. The research highlights consideration for builders, developers, architects, and design professionals in the context of designing buildings with 3DCP technology, contributing to a better understanding of the challenges and opportunities in the adoption of innovative construction methods.

Solomon Greene
Principal Deputy Assistant Secretary for Policy Development and Research
U.S. Department of Housing and Urban Development

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Executive Summary

This report provides an overview of three-dimensional concrete printing (3DCP) technology, which is a new construction method using robotics to build structures with concrete material that does not require traditional concrete form work. Five types of 3DCP technologies exist—gantry, robotic arm, robotic crawler, polar, and delta—and this report describes each type and where they are commonly used. In addition, the authors identify the leading 3DCP companies and how to acquire their technology.

During this research project, the authors convened an advisory group of key stakeholders to review 3DCP construction practices, technical requirements, and the challenges of integrating 3DCP technology into a conventional construction process. The team highlighted key issues—such as contracts, warranties, design options, building code compliance, and installing building products—that builders and developers must consider when incorporating 3DCP technology.

The research indicates 3DCP technology has the potential to significantly change the homebuilding process in terms of labor requirements (different skill sets and fewer people), aesthetic wall exterior (how to install conventional cladding products if preferred), the construction process (no more 2x4 framing for walls), and how best to demonstrate code compliance when building code does not yet recognize the technology—to name a few. Because the construction industry is often slow to adopt new technology, education and instruction will be needed on how best to integrate 3DCP technology for builders accustomed to building the conventional way.

3DCP companies have proprietary technology that is not defined based on a single voluntary standard. The American Concrete Institute and National Institute of Standards and Technology have led the effort to standardize materials, performance metrics, and robotics, but it has been a slow process. Currently, no trade association formally represents the 3DCP technology industry. The areas of robotics, supporting equipment, material formulation, and construction practices need more standardization, and this standardization is typically achieved through publishing industry-endorsed design guides and third-party standards and establishing good manufacturing practices.

Early adopters of 3DCP technology will need to be aware of the proprietary nature of the technology and the limitations it may present in terms of equipment service support, replacement parts of robotic components, long-term warranties, and the longevity of companies. Builders and developers must consider workforce development and training needs when integrating 3DCP technology into conventional stick frame construction for the following reasons:

- The skills required to operate and maintain robotics are different than the skills of the carpenters (i.e., framers) and masons that the technology will replace. In fact, fewer employees may be needed to operate robotics, and these new skills may command higher salaries compared with carpenters or masons.
- 3DCP companies understand how to print structures, but many lack an understanding of the homebuilding process and how their technology may change wood-framed construction. Currently, most 3DCP companies see themselves as providers of this new construction technology, not partners with builders or developers. Comprehensive education is needed on the basics of construction and how robotics can improve the process.

- 3DCP will change how homes are built, because coordination and sequencing of existing construction trades, such as plumbers and electricians, will be different when robotics are integrated on the jobsite.

HUD has studied innovation in construction as a means of achieving better affordable housing. 3DCP technology offers a solution to labor shortages in construction and may be one method of increasing the housing inventory. Nonetheless, 3DCP technology is not yet optimized for conventional construction, and too few houses have been built using the technology to identify "best practices." HUD is uniquely positioned to work with the industry to develop building code and design guidance and opportunities for collaboration among the various stakeholders. During this initial period of technology development, more collaboration is needed between the builders, developers, and 3DCP technology companies.

The authors recommend more research to define the labor requirements and construction costs. Currently, the available data are incomplete and not useful for benchmarking or comparative analysis with common construction practices. A major predictor of wide-spread adoption of a new building technology is construction cost and the ease of implementation.

Introduction

This research project investigates three-dimensional concrete printing (3DCP) technology by exploring two key construction issues. First, the authors identify barriers to adopting 3DCP technology, such as the lack of building codes or standards, design and construction guidance, and the technical expertise to implement the new technology. Second, the team describes typical construction practices needed to integrate 3DCP technology into conventional construction by evaluating the installation of 3DCP walls with conventional building product components.

Two volumes present the research findings. *Part 1: Identifying Barriers and Opportunities* summarizes the qualitative market research results based on focus groups and surveys with home builders and contractors. The team explores the challenges and opportunities of accelerating the adoption of 3DCP technology. *Part 2: An Overview of 3DCP Construction Practices* provides builders, contractors, and developers with information about installing 3DCP technology.

This report is the technical portion of the research, and it serves as a primer for 3DCP technology. Builders and developers will learn about 3DCP technology options and the typical construction practices used to integrate 3DCP structures with conventional building products. Because the options for builders and developers to consider are many when selecting 3DCP technology, the team developed a checklist highlighting key questions for builders and developers to consider when discussing options with 3DCP technology manufacturers. Generally, 3DCP technology is proprietary, and costs are not standardized for comparison with typical construction practices, so much diligence is required when considering options.

Background

Concrete is the most widely used building material in the world (Zilliacus, 2016), and three-dimensional concrete printing (3DCP) technology has the potential to significantly change how buildings are delivered using new robotic construction techniques. With this technology, concrete is formulated to achieve greater workability, setting, hardening time, and mechanical properties, which can be optimized for the specific building requirements. These attributes make innovative structural design possible using a 3D concrete printer that extrudes concrete material layer by layer without any formwork support. Several buildings around the world have been successfully erected using 3DCP technology and in a wide range of applications—from affordable housing to multifamily buildings and to military structures.

Currently, most 3DCP technology research focuses on standardizing the equipment design, manufacturing process, and material formulation (Buswell et al., 2018). The National Institute of Standards and Technology leads this research effort in collaboration with the American Concrete Institute and various universities. The research is critical to improving the quality and reliability of 3D concrete printed structures, but understanding how this new technology must be integrated into conventional construction practices is equally important. The team provides an overview of 3DCP technology options and a short description of its major manufacturers.

3DCP Technology Options

3DCP technology is a fast-growing construction method that aims to address construction labor shortages and the affordable housing crisis. The 3DCP manufacturers profiled here offer several types of innovative robotics to automate both exterior and interior wall construction. At the time of writing this report, the following 3DCP technology options have been identified:

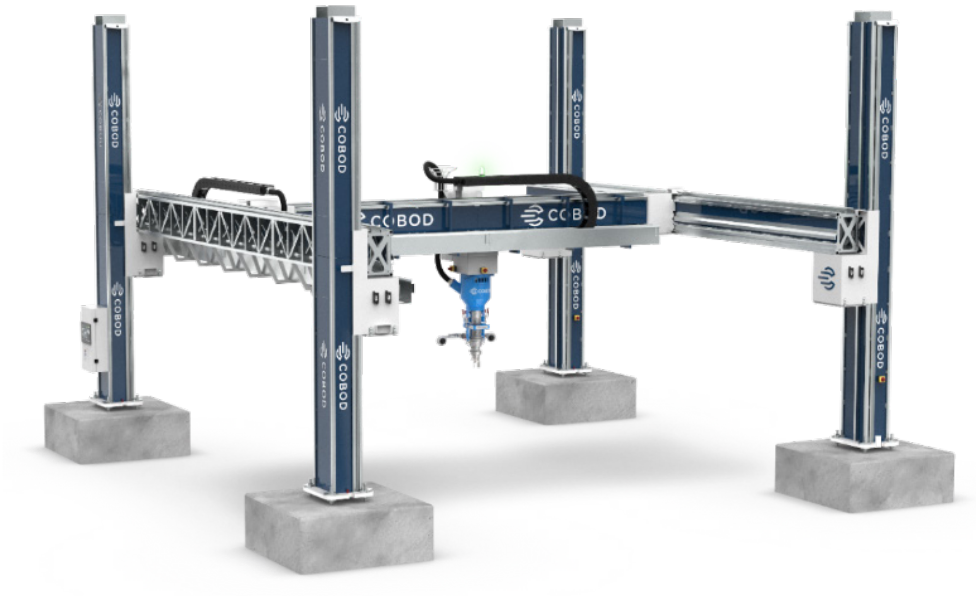
- Gantry.
- Robotic arm.
- Robot crawler.
- Polar.
- Delta.

This report defines each type of printer, knowing that advancements in technology happen rapidly and may change within the next 3 to 5 years.

Gantry

Gantry-style printers have the main robotic component mounted on a horizontal frame, with supports on each side such that the printer can span and move over the building being printed. Gantry is the most widely used type of 3D construction printer in the industry. COBOD is the primary manufacturer of gantry-style printers (exhibit 1). Black Buffalo 3D Corporation also makes a gantry-style printer called the NEXCON™ that can be installed and leveled without concrete footings (exhibit 2). Gantry-style printers can build external and internal wall sections in a fraction of the time needed for normal construction. They require careful assembly and using additional industrial equipment, such as cranes for hoisting and semi-trailers for hauling the modules for assembly.

Exhibit 1. COBOD BOD2 Construction Printer



Source: COBOD

Exhibit 2. Black Buffalo 3D Corporation's NEXCON™ Printer

NEXCON Gantry Printer. Photo credit: Black Buffalo 3D (2022).

The gantry-style printer requires a large framework depending on the home's footprint and must be able to encompass the structure, an important consideration for the required lot size. The lot, or more importantly the slab (in some cases), must be able to support the deadload of the structure and the more dynamic weight of the operating printer as it constructs wall sections. Several companies have completed projects with the exterior walls printed first, then pouring the slab inside the printed structure. Depending on the structure's size, slab aprons and concrete footers may be necessary to adequately secure the printer during construction. This report later discusses these equipment requirements and how they affect the site design.

Compared with other printers, gantry-style printers will likely incur higher additional site, transportation, maintenance, depreciation, setup, and breakdown costs. Site construction costs may increase due to the addition of slab aprons and concrete footers. Transportation costs will include the additional semi-trailer trucks needed for the modules of the frame assembly. Maintenance and depreciation costs are estimated to be higher due to the constant assembly and disassembly of components, a common consideration for mechanical equipment. Finally, the setup and breakdown of gantry printers require more equipment, time, and coordination than other types of printers on the initial setup. If the printable area can leverage a gantry system on rails, then the setup time for a larger project would require less time than other printer types. After completing construction, the builder must decide if any concrete footers or anchoring that may be required for some gantry and robotic arm printer's framework or base should be left in place.

Robotic Arm

Robotic arm printers are predominantly used in laboratories and in demonstration settings. They are compact and do not require the large framework of their gantry-style counterparts. A pickup truck and trailer can usually transport robotic arm printers to the field. Exhibit 3 shows a robotic arm printer mounted on a platform that can be adjusted vertically. The platform has wheels that allow it to move horizontally on a track as the robotic arm prints the concrete structure.

Exhibit 3. RIC Technology's RIC-2 (Field Robotic Arm Printer)

RIC 2 Robot Constructing Wall. Photo credit: RIC Technology (2022).

Although limited in print radius, robotic arm printers are capable of printing walls in multiple sections by repositioning the robot on the platform. Compared with a gantry-style 3DCP robot, repositioning the robotic arm is easy due to its size and weight. The printer must also be able to be removed from the inside of any printed area or be limited to printing a single side of the wall. Robotic arms can build a wide range of building wall configurations, but the height of the building will be limited to the platform and how the arm configuration. With an average weight of about 1 ton, lifting the robotic arm to increase the wall height requires additional equipment and a level of precision that is difficult to achieve without jeopardizing cost-savings and safety.

Compared with other printers, robotic arm printers will likely incur minimal additional site, transportation, maintenance, depreciation, setup, and breakdown costs. Site and transportation costs will be negligible due to the printer's compact and portable nature. Maintenance and depreciation costs will vary by printer but benefit from not being assembled and disassembled repeatedly. Setup and breakdown of robotic arm printers is usually negligible but must account for concrete footers in rare cases, or some may need to be anchored to a slab for stability.

It is important to consider how many positions a project will require when using robotic arm printers. It takes about 45 minutes on average for two laborers (and additional equipment) to reposition and configure a robotic arm printer during construction. The manual repositioning conflicts with automating construction, adding time and human error to the process, with a great impact on operational costs. Robotic arm printers are also limited in their ability to control output and start and stop functions during printing. This inability limits the programable print path to connect sections compared with several gantry systems, including COBOD BOD2 and Black Buffalo's NEXCON printers, which are capable of starting and stopping for printed openings such as windows; doorways; and optional mechanical, electrical and plumbing openings in walls.

Robot Crawler

Robot crawler printers are the more mobile brother of the compact and portable robotic arm printers. They are still transported with ease to jobsites, with the added benefit of continuous treads, similar to a tank or continuous track vehicle. Exhibit 4 shows this design feature and that navigating around jobsites is easy because a track and platform are not needed. Any repositioning of the robot crawler is less complicated than using the robotic arm or gantry-style printer.

Exhibit 4. CyBe Construction's CyBe-Robot Crawler

Mobilizing the CyBe Robot Crawler.
Photo credit: CyBe (2022).

The print radius is still limited with robot crawler printers, but repositioning can be automated due to the continuous tracks. Robot crawler printers tend to have a larger minimum print radius due to longer arms compared with robotic arm printers. The print design must still account for mobility to confirm that the crawler can exit any structure that it prints.

The printers also offer a hydraulic system to extend the vertical reach of the printer, allowing for greater wall heights compared with robotic arm printers. A caveat is that hydraulic systems tend to lack the level of precision needed for 3DCP construction, and tall wall sections should be carefully monitored during construction.

Robot crawler style printers will likely incur minimal additional site, transportation, setup, and breakdown costs compared with other printers. Site, transportation, setup, and breakdowns costs will be negligible due to the printer's compact and portable nature.

Although it will still take an average of about 45 minutes for printer reconfiguration and repositioning, the process can be completed with one laborer and no additional equipment due to the continuous tracks and automation of the mobile printer. These features greatly reduce the operational costs compared with robotic arm printers, but maintenance and depreciation costs increase greatly with the inclusion of hydraulic machinery.

Polar

The polar printer is aptly named for the patented coordinate system from which it operates. The printer's functionality has both the robotic arm and robot crawler printers' design elements. The printer is easily transported to job sites and designed specifically to print within a standard residential building lot size. Apis Cor Inc.'s polar printer is compact enough to fit through a 4-foot-wide opening (exhibit 5).

Exhibit 5. Apis Cor Inc.'s "FRANK" (Polar Printer)

Frank is small, mobile, and easy to operate. Photo credit: Apis Cor (2023).

The printer has a limited print radius compared with gantry-style printers but has the same ability for autonomous repositioning around a home's floorplan as robot crawler printers, without the use of hydraulic systems. Polar printers can print higher wall sections due to the telescopic chassis, allowing a maximum wall height of 10.5 feet.

The polar printer will likely incur minimal additional site, transportation, maintenance, depreciation, setup, and breakdown costs compared with other printers. Site and transportation costs will be negligible due to the printers' compact and portable nature. Maintenance and depreciation costs are minimal, and the simplicity aids cleaning the printer. Some parts are fully autonomous. The setup and breakdown of the polar printer is usually negligible, but in rare cases can include the need for hoisting the printer via crane.

It is important to consider how many positions a project will require when using the polar printer. It takes about 45 minutes on average for a laborer to reposition and configure the printer during construction, which will affect a project's operational costs.

Delta

Delta printers are similar to gantry-style printers, because the robotic component is mounted on a framed structure (exhibit 6). The delta printer can accommodate more than one robotic component, but it typically prints round igloo-shaped structures. The Delta printers are predominant in additive manufacturing of non-cementitious material such as plant-based biomass and pulp materials. Delta printers have generally been used because of their quick print times. The quick print times associated with the printers usually correspond with less accurate builds, perfect for prototypes and rough builds but not ideal for 3DCP construction, and the time it takes for cementitious mortar to cure is likely a factor in the printers' limited industry penetration.

Exhibit 6. Crane WASP (Delta Printer)

The WASP builds round structures. Photo credit: Crane (2022).

Delta style printers require careful assembly and using additional industrial equipment, such as cranes for hoisting and semi-trailers for hauling the modules for assembly. The delta printer requires a large framework dependent on a home's footprint and must be able to spherically encompass the structure, an important consideration for the required lot size. The lot, or more importantly the slab, must be able to support the deadload of the structure and the more dynamic weight of the operating printer as it constructs wall sections. Depending on the size of the structure, slab aprons and concrete footers may be needed to adequately secure the printer during construction.

Delta style printers will likely incur higher additional site, transportation, maintenance, depreciation, setup, and breakdown costs than other printers. Site costs will increase due to the addition of slab aprons and concrete footers. Transportation costs will include additional semi-trailer trucks needed for the frame assembly modules. Maintenance and depreciation costs are estimated to be higher due to the constant assembly and disassembly of components, a common consideration for mechanical equipment. Finally, the setup and breakdown of delta printers require more equipment, time, and coordination, making them similar to gantry printers.

3DCP Technology Companies in the United States

3DCP companies include printer manufacturers and builders and distributors of technology, equipment and materials. At the time of writing this report, the team identified the following companies. These companies were selected based on their time in the industry, the number of buildings they have constructed in the United States, and their stated goals to build community-level developments. This is an emerging industry. As a result, the team expects more companies to enter the market; some may leave, and others may merge. In short, this report does not endorse any company nor the claims they make (which may change given the rate of innovation observed during the 3-year research period).

COBOD

COBOD is the leading manufacturer of 3D concrete printers, with its BOD2 gantry printer being the most used printer worldwide.[1] COBOD already has a network of builders across the world, and within the United States, they supply ALQUIST and PERI 3D Construction with equipment and training.

Black Buffalo 3D Corporation

Black Buffalo is a leading manufacturer of 3DCP printers within the United States and offers training and services to home builders in their network.[2] The NEXCON gantry printer constructs wall sections in a fraction of the time required to build a conventional concrete masonry unit (CMU) wall. Black Buffalo 3DCP has the first evaluation service report (ESR), ESR-4623, from the International Code Commission Evaluation Service (ICC-ES) based on Acceptance Criteria (AC)509, which is a means to demonstrate building code compliance (ICC-ES, 2023a). Black Buffalo has several partners that manufacture its proprietary ink. In North America, the company partners with MAPEI Corporation to manufacture and distribute its ICC-ES- and AC509-approved material to any 3DCP company, whether they use NEXCON printers or other 3DCP technology. The material is a dry ready mix that only needs water added when on site.

ICON Technology, Inc.

ICON is a leading 3DCP company that offers a turnkey approach to development.[3] ICON does not sell printers nor provide training. Instead, they can be hired to complete an entire development with their gantry printer, the Vulcan Construction System. ICON has the second ESR, ESR-4652, from ICC-ES based on AC509, which is a means to demonstrate building code compliance (ICC-ES, 2023b).

Apis Cor Inc.

Apis Cor is the leading 3DCP manufacturer not using a gantry printer. Instead, Apis Cor stands by their patented polar printer (codenamed FRANK), with the goal of helping to solve the worldwide housing crisis. Apis Cor has a unique approach to demonstrate building code compliance. Rather than prove each printed wall is structurally equivalent or improved compared with masonry or concrete wall sections, Apis Cor elicited a third party to research and demonstrate that their 3DCP construction is equivalent or better than CMU block framing (NFPA, 2020).

ALQUIST

ALQUIST is a building and design firm, with the mission of using 3D technology to optimize design and affordability in response to the housing and infrastructure crisis in economically

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[1] https://cobod.com/.
[2] https://bb3d.io/.
[3] https://www.iconbuild.com/.

distressed and underserved communities.[4] In partnership with the Virginia Habitat for Humanity, ALQUIST has already completed four homes in Virginia (in Richmond, Williamsburg, and two in Newport News) in support of their mission, using both the BOD2 and NEXCON gantry printers. The Newport News homes used the Black Buffalo NEXCON printer to construct the first structural walls without infill or rebar reinforcement. The MAPEI Corporation manufactured the proprietary material, Planitop 3D [NA].

PERI 3D Construction

PERI is a leading provider of 3DCP construction worldwide, with the goal of revolutionizing the construction industry.[5] PERI already has an impressive library of finished projects across Europe and plans to build more in the United States. The company uses the BOD2 printer to provide unique and energy efficient homes at an affordable rate.

Crain Company 3D LLC

Crain Company is a new home builder that adopted 3DCP technology to improve speed and efficiency in the building process.[6] They believe that 3DCP technology can be a solution to the global housing shortage. The company is in the process of developing the first 3D printed community in Kansas.

Emergent

Emergent is a new home builder focusing on expediting rebuilding homes in Northern California in response to the Carr Fire disaster recovery efforts.[7] They believe that 3DCP technology can provide homes quickly that are more resilient to future fires. The company has built three 3DCP homes using the COBOD gantry-style printer.

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[4] https://www.alquist3d.com/.
[5] https://www.peri.com/en/business-segments/3d-construction-printing.html.
[6] https://crainco3d.com/.
[7] https://emergent-3d.com/about-emergent.

Acquiring 3DCP Technology

Builders and developers have several options from which to choose when considering and selecting three-dimensional concrete printing (3DCP) technology to integrate into their construction process. If they have experience using concrete masonry units (CMUs) to construct residential buildings, then the transition to 3DCP technology may be easier because the installation techniques are similar, even though the method of applying the concrete material is different—for example, using robotics to place concrete extrudate versus concrete masons laying CMUs with mortar. For builders primarily using lumber for stick frame construction, the team believes that the learning curve will be steeper because builders will need to (1) convert from wood to concrete material and (2) learn how to integrate robotic technology into their construction process. In either case, it is important to note that 3DCP technology replaces the conventional construction labor and materials to build walls.

Builders or developers interested in using 3DCP technology may engage these companies in one of three ways:

1. **Vertically Integrated Company.** A 3DCP technology company is vertically integrated when it manufactures the material and robotics and builds the entire house. This process might be ideal for developers that want to see "how" 3DCP technology differs from conventional construction, and it may be the easiest way to see the entire process from start to finish. By contracting with a vertically integrated company to build an entire neighborhood or to provide select houses within a larger development, the developer can determine if 3DCP technology is right for them without directly investing in the technology.
2. **Subcontract.** Subcontracting with a 3DCP technology specializing in 3DCP technology construction might be ideal for builders who want to use the technology but not invest in purchasing it. In this case, hiring a 3DCP technology company that builds only walls is not much different than hiring a framing crew, concrete masonry company, or any other subcontractor on a construction site.
3. **Purchase or Lease.** Builders or developers acquire 3DCP technology by either purchasing or leasing robotics and materials from a 3DCP technology company. This process might be ideal for builders who want to own the technology and market their company as a 3DCP builder or subcontractor. For builders who decide to purchase or lease the technology, it is important to have technical support from the 3DCP technology company. Builders will have to know what to do if the machine breaks down, how it must be maintained or serviced, how to get software or hardware updates for the robotics, how the material must be stored and the lead time for delivery, how builders will train construction crews to use the technology, and if the 3DCP company goes out of business, how the robotics will be serviced and even if material will be available. The builder must consider these questions before making a major purchase decision.

Contracts

Standard contracts govern residential construction that establish responsibilities for each party, workmanship expectations, and a legal framework for resolving disputes. The National Association of Home Builders (NAHB) provides several residential construction contracts, exclusively for home builders and remodelers. These contracts are a good starting point for developing agreements with 3DCP technology companies.

Builders and developers must be aware that many of the 3DCP companies may have very little experience with the residential construction industry; as a result, those companies may not be familiar with typical contracts used by builders, including standard NAHB subcontractor agreements (NAHB, n.d.). In some cases, builders and developers may have to educate 3DCP technology companies on the standard terms for construction and the role of each party. Because 3DCP technology is proprietary, and no industry standards exist, each contract needs to be developed and customized with an attorney's assistance.

Liability

3DCP technology companies will have to educate builders and developers on what constitutes a manufacturing defect in terms of the equipment, robotics, material, and final printed wall. At least six anticipated hypothetical issues may lead to construction or manufacturing defects.

1. **The equipment/robot is not functioning correctly.** In this case, does the 3DCP technology company provide technical support to trouble-shoot and repair the robot? If defective robotics produce a defective wall, which party is liable for replacing the wall? How would one determine if the printed wall is defective—that is, which cracks are cosmetic versus indicative of a structure problem?
2. **Personnel do not operate the equipment/robot correctly.** If human error occurs when setting up or operating equipment, does the equipment provide real-time feedback indicating that the equipment is not operating within design parameters? If operator error produces a defective wall, which party is liable for replacing the wall? How would one determine if the printed wall is defective—that is, which cracks are cosmetic versus indicative of a structure problem?
3. **The material does not meet the specification.** If the concrete material is delivered out of specification or if the concrete material mix was prepared incorrectly on site, which party is responsible? If this error leads to printing a defective wall, which party is liable for replacing the wall? How would one determine if the printed wall is defective—that is, do nondestructive tests exist to assess the wall's structural integrity?
4. **Installing other building products into the wall incorrectly.** 3DCP walls must be able to accommodate installing conventional building products—such as windows, doors, floors, roofs, and other components—or custom products must be developed specifically for 3DCP walls. Generally, manufacturer installation instructions must be followed for product warranties to be valid. As a result, if a window develops a leak because the window could not be installed correctly in an exterior 3DCP wall, which party is liable for repairing or replacing the window? If the 3DCP wall is structurally sound, but other building products typically found in the wall start to fail or perform poorly, the remedy can be expensive and time consuming.
5. **Prefabricated 3DCP components are manufactured in plants and delivered to builders and developers for assembly on site.** If the builder or developer receives prefabricated components, the liability may shift from being based on field construction to field assembly, which also shifts traditional construction defect risks to product liability risks (like any other purchased building product). This shift will affect how risk

is allocated between the contractors and their manufacturing partners and how projects need to be insured.

6. **Sustainability and Environmental Performance Claims.** When these claims are made and determined to be misleading or unsupported, who is liable and can the risk be managed with insurance?

All parties (builders, developers, and 3DCP manufacturers) should consider liability in terms of "who is responsible for what." More than one contract type may be needed, depending on what the 3DCP company does versus the technology's builder or purchaser. In any case, the responsibility and liability should be well defined within the contract to avoid confusion or disputes if problems arise during the construction process. Insurance might be necessary to ensure that manufacturing defects can be remedied if the 3DCP manufacturer does not have the capacity to be self-insured.

Warranty

Generally, 3DCP technology companies offer warranties for any leased or purchased equipment or robotics. The warranties vary and may depend on whether the purchaser enters into a service agreement with the 3DCP manufacturer. This decision will be an important consideration for any builder or subcontractor that decides to invest in the technology. The technology is expensive to purchase, starting at $800,000 (Purcell, 2022).

Equally important, builders and developers will need to educate 3DCP technology companies on the expectations of new home buyers. Generally, a new home comes with a builder's warranty against construction defects. For most construction components, the builder will rely on the manufacturer's warranty, and the terms of a warranty vary based on the product type. Nonetheless, it is common for a home builder to provide a 10-year warranty against structural defects.[8] These warranties are defined to distinguish between cosmetic issues and structural problems. Large builders may provide these warranties through their companies, and mid-sized or smaller builders may use a third party to provide a structural warranty. In any case, 3DCP technology companies should be aware of these expectations, because their robots will be building the load-bearing parts of the building if they have not incorporated other structural reinforcement elements, and they should consider how best to demonstrate that their 3DCP walls can meet the expectation of long-term performance.[9] NAHB (2023) developed a document entitled Assessing Building Materials to guide builders or contractors when considering a new construction material supplier.

[8] See https://www.2-10.com/builders-warranty/structural-warranties/ for an example of a structural warranty.
[9] See the exhibit A-2 checklist for builders and developers to use when considering questions to ask 3DCP technology companies.

Design Considerations for Residential Construction

Builders and developers must be aware of two design considerations: (1) the lot size needed to construct with three-dimensional concrete printing (3DCP) technology and (2) the details of the building plan, with special attention being paid to the locations of electrical and plumbing utilities. Generally, 3DCP technology requires a slightly larger lot size compared with conventional stick frame and concrete masonry unit (CMU) construction, because the lot must accommodate the building being constructed and the space needed for the robotics and related equipment. The lot size requirements will vary based on the 3DCP technology selected and the residential building design. Builders and developers must work closely with 3DCP technology companies to ensure that land and lot size requirements are considered. In places where land is expensive, the added space requirements could equal 5 to 10 percent of additional land for the increased lot size. To further illustrate the lot size requirements, the following is a general analysis of gantry and delta printers.

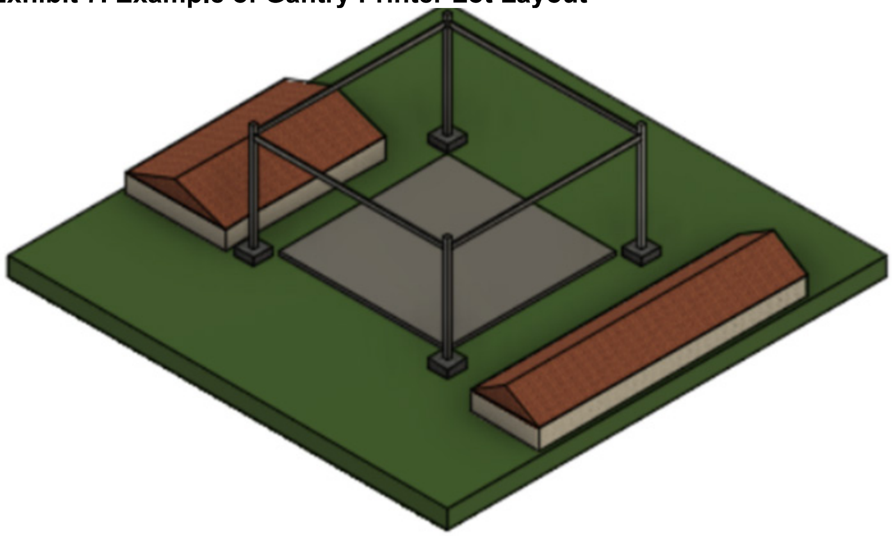
Components of a gantry-style printer will be shipped via semi-trailer with the accessory equipment and supplies needed for the project. The equipment will be lifted from the truck to an erect position via crane. The assembly surface must be level and able to support the roughly 19-ton weight of the typical printer.[10] Generally, the printer is assembled on the building's slab, but concrete footers can be placed on any level surface capable of supporting the printer's load to avoid making a slab larger than what is required for the building.

A batch plant or mixing station will be necessary near the printer for the concrete material, along with a material pump to deliver the printed material. The printer will also need access to a water source. If not available, then water storage or tanks will be necessary, requiring additional space. To load the mixing station, industrial vehicles may be necessary for transporting material and accessing the loading site.

If assuming a 45x45-foot (2,025 square feet) slab, one can estimate that the layout of a gantry printer constructed on a 118x118-foot (0.3 acre) lot will require a 57x57-foot printer module framework around the foundation, with an average semi-trailer truck measuring 72x8.5 feet (model dimensions are 72x18 feet for additional storage) and the estimated storage for accessory equipment for the printer at 43x27 feet. Exhibits 7 and 8 illustrate an example of the lot size planning and logistics necessary for the gantry printer.

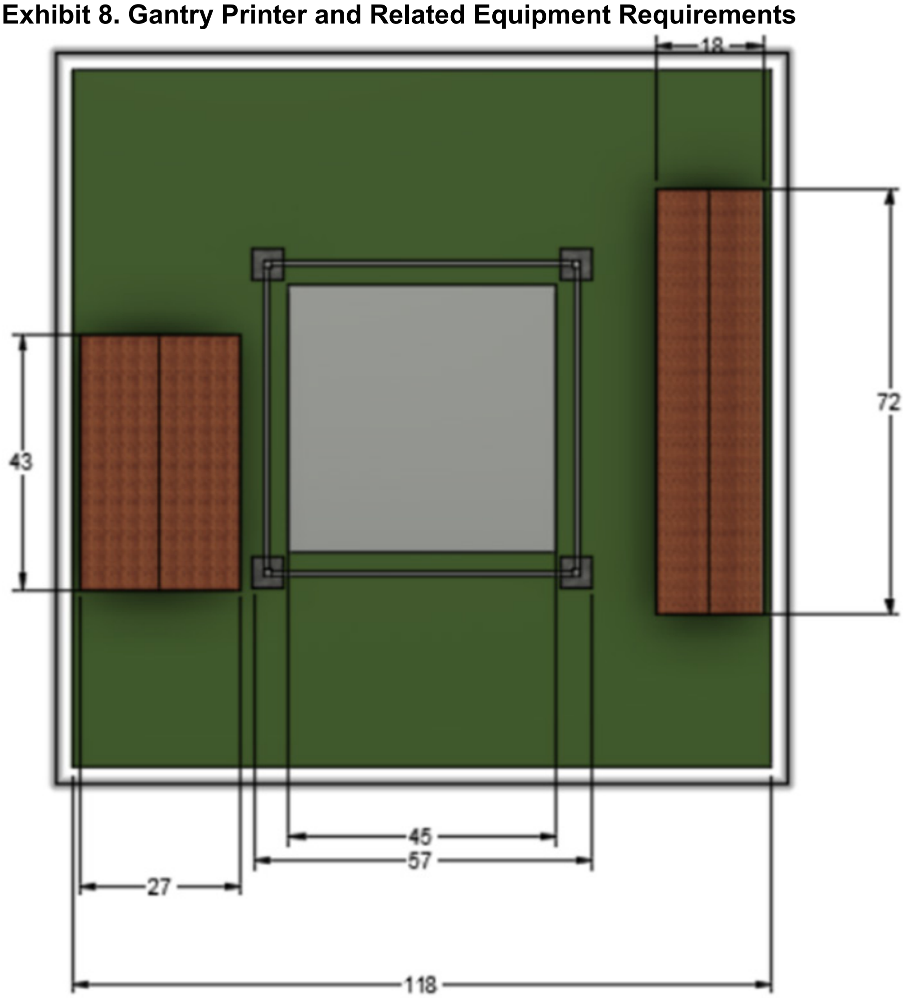
[10] The weight will vary based on the 3DCP technology. A builder or developer must work with the 3DCP technology company to get specific details about using particular printers.

Exhibit 7. Example of Gantry Printer Lot Layout



Source: Home Innovation Research Labs

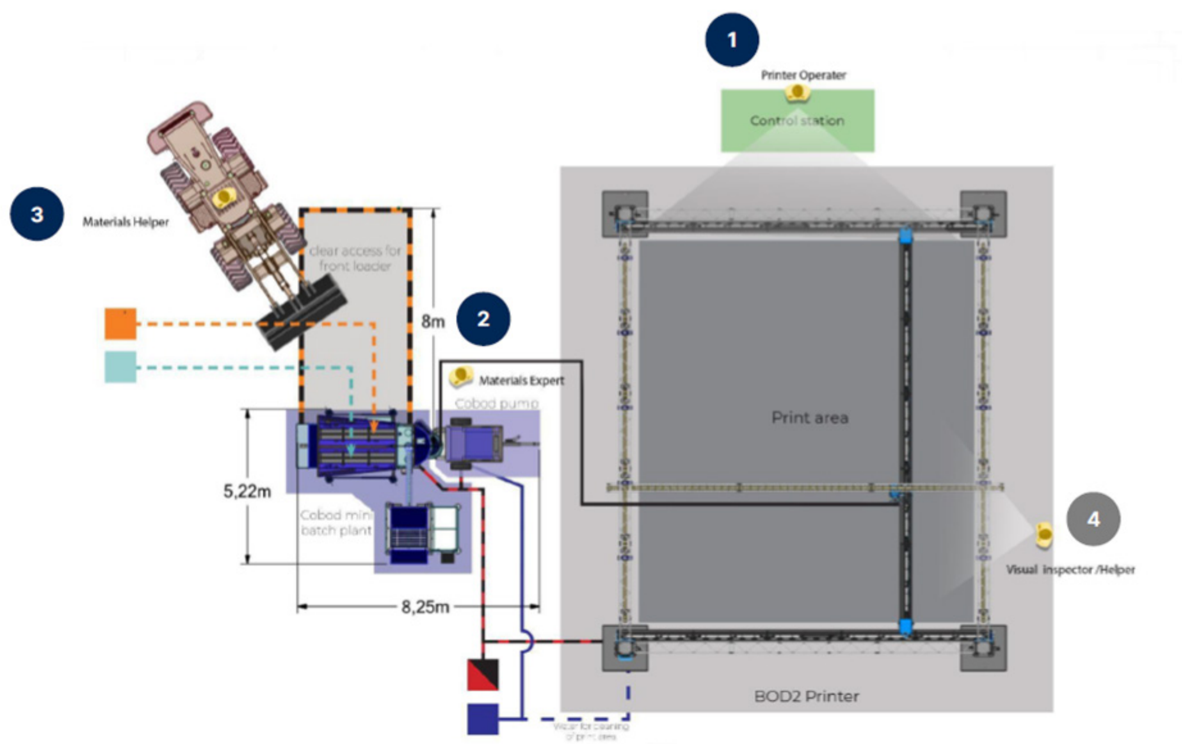
Exhibit 8. Gantry Printer and Related Equipment Requirements



Source: Home Innovation Research Labs

COBOD, the major manufacturer of 3DCP gantry technology, works closely with builders and developers to ensure that site plans are optimized for residential buildings to verify meeting space requirements. Exhibit 9 illustrates BOD2 gantry printer requirements, highlighting the locations of the printer's supporting equipment and operators.

Exhibit 9. BOD2 Printer, Equipment, and Labor Requirements for Lot

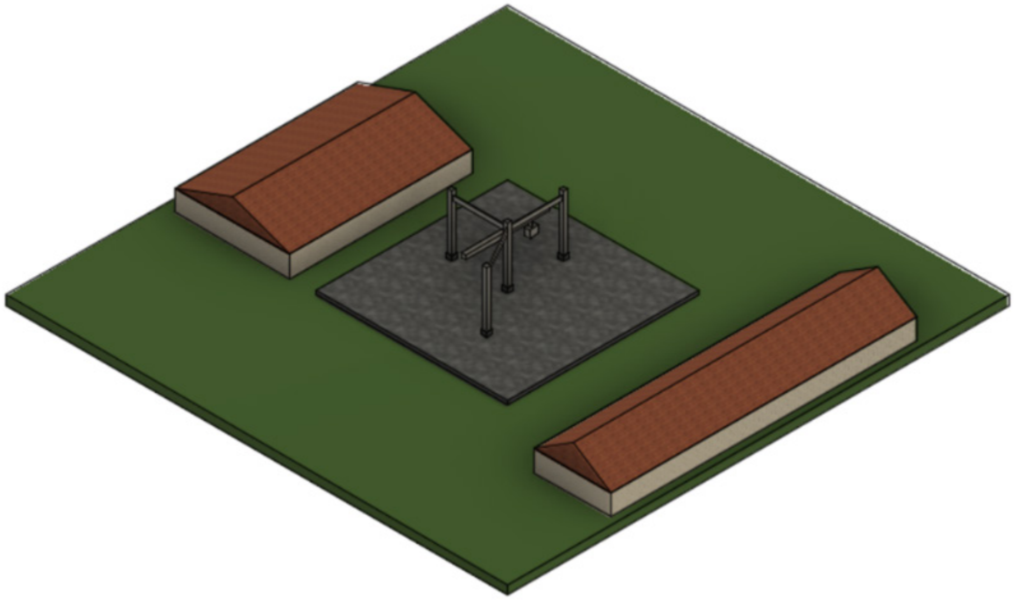


Source: COBOD

The BOD2 gantry printer requires one operator to run the printer from the control station, one operator to run the material pump, one operator to feed material into the pump, and one inspector to ensure that the robotic printer produces a high-quality printed structure.

The transportation and assembly requirements of the delta printer are similar to those of the gantry-style printer. However, the typical weight of the delta printer is roughly 10 tons, about half the weight of the gantry-style printer. In addition, the delta printer is generally assembled on a slab surface to print a wall structure (exhibit 10).

Exhibit 10. Example of Delta Printer Lot Layout

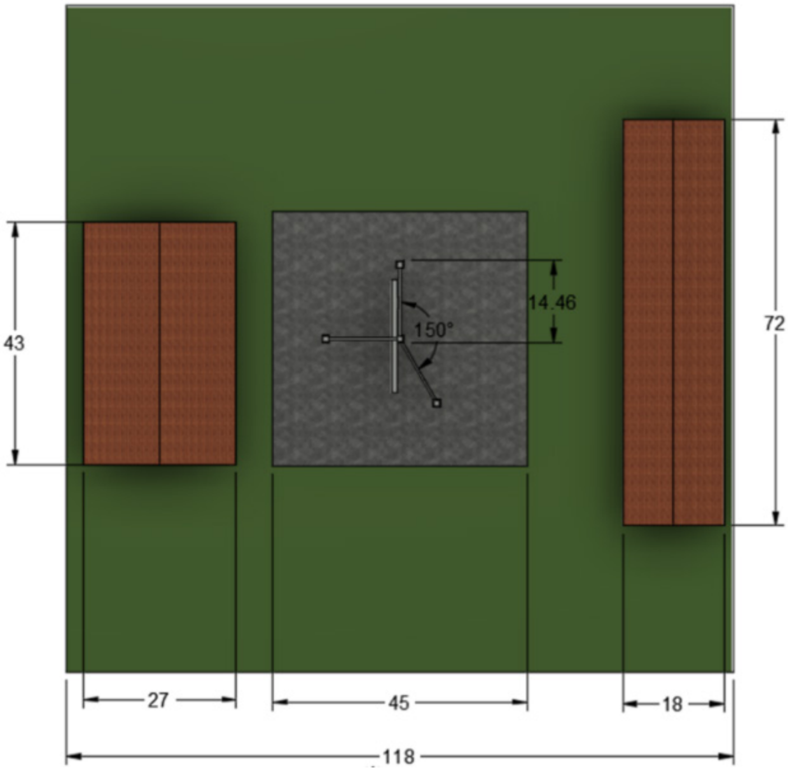


Source: Home Innovation Research Labs

Similar with the gantry-style printer, material needs to be batched and mixed using additional equipment, such as a batch plant or mixing station. In addition, the builder will need a source of water, which will take up additional space. If the water comes from a municipal source, the backflow preventors certainly must be installed, and other precautions must be taken given the industrial application of mixing concrete to print.

Using a 45x45-foot (2,025 square feet) slab, the possible layout of a delta printer constructed on a 118x118-foot (0.3 acre) lot is similar to the gantry-style printer, with the expectation of similar accessory equipment. Therefore, a semi-trailer truck measuring 72x8.5 feet (model dimensions) will have to be added for additional storage. Exhibit 11 shows the estimated storage at 43x27 feet.

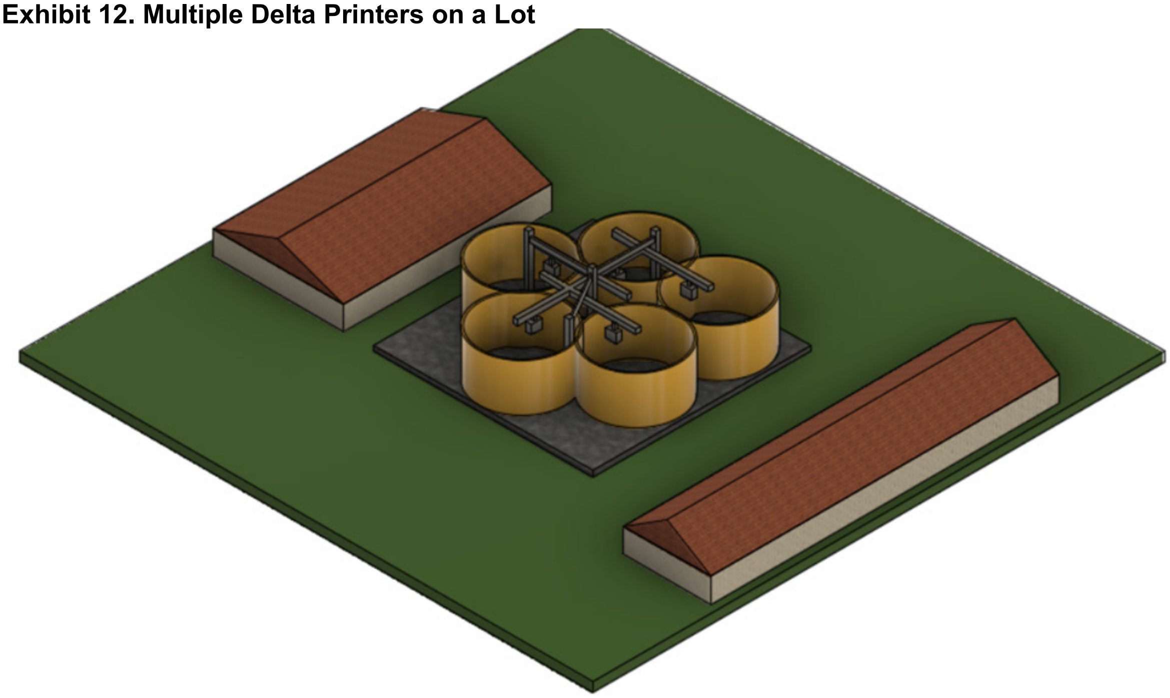
Exhibit 11. Delta Printer and Equipment Requirements



Source: Home Innovation Research Labs

Using delta printers will require developers to build nonrectangular wall structures, something resembling an igloo. The printing arm configuration can be combined with multiple printers to approximate a rectangular walled building (exhibit 12).

Exhibit 12. Multiple Delta Printers on a Lot



Source: Home Innovation Research Labs

Builders and developers must consider a printer's capability to print a conventional rectangular shaped building, which may vary based on the 3DCP technology, or ask if home buyers will consider purchasing a house that is nonrectangular.

Beyond the building's footprint, one stated value proposition of 3DCP technology is incorporating multiple features into the wall cavity—such as printing plumbing chases and electrical conduit openings. Doing so will require a level of design detail that is not common for many builders, because the carpenter, plumber, and electrician have some tolerance they can work that may not be the "exact" location shown on the drawing.

For 3DCP technology, the locations are exact, not approximate. If a discrepancy appears during the design phase, or if a utility company does not correctly place the water or electrical services in a specified location, it may lead to construction problems.

The 3DCP technology and programing needs of the robotics may drive some design requirements. This design consideration will be different from conventional stick frame and CMU construction but could lead to greater quality and consistency in the final building construction.

Building Code Compliance Options

Generally, three options demonstrate building code compliance.

1. Prescriptive compliance with the requirements in the local building code.
2. Alternative means and methods to demonstrate compliance with local building code.
3. Evaluation service reports demonstrate that new materials or construction methods meet the requirements of the model building code based on products developed under a quality control program with repeatable performance results.

Most conventional construction is permitted under the first option, using materials and construction methods defined in the local building code (generally, a prescriptive approach). For example, wood frame construction is well-defined in the building code and referenced standards used by the building code. Architects, engineers, and builders who use the defined materials, reference standards, and design guidance in the building code can easily demonstrate compliance, such as meeting or exceeding the requirements, with most building code officials.[11]

Some commercial construction and custom "one-of-a-kind" projects are evaluated for building code compliance using the second option, alternative means and methods (IBC, 2021),[12] which relies on a combination of architectural and engineering design calculations and material test data for new materials or construction products not defined in the building code. Generally, this approach is performative to demonstrate building code compliance, which relies on technical analysis and review with the authority having jurisdiction.

New building products and construction methods use the third option. Evaluation service reports (ESRs) are technical reports that evaluate the performance of new building products and construction methods based on a test protocol that demonstrates code compliance.[13] The third option allows manufacturers and building product companies to have innovative materials and construction processes independently evaluated and instructions for installation provided such that the authority having jurisdiction can be assured of repeatable performance results. This step is typically a precursor to having a new building material or construction process added to the model building code.

Virtually all buildings constructed using three-dimensional concrete printing (3DCP) technology in the United States have been built under option 2, using the alternative means and method process for code compliance. The International Code Council Evaluation Services (ICC-ES) developed a relatively new Acceptance Criteria (AC)509, 3D Automated Construction Technology for 3D Concrete Walls, for evaluating 3D wall construction (Ekenel and Sanchez, 2019). In October 2022, Black Buffalo became the first 3DCP technology company to codify their material and printing process with an ESR. The ICC applauded ESR-4623 as "giving code officials peace of mind while approving such a method of construction, knowing the product has

[11] The authority having jurisdiction, the local building code department, interprets whether designs, drawings, and specifications meet the prescriptive methods of compliance with the building code.
[12] The authority having jurisdiction states that "an alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety."
[13] The International Building Code Council's Evaluation Services (ICC-ES) division issues ESRs that the authority having jurisdiction generally accepts during permit and code compliance reviews.

met the rigorous requirements of ICC-ES" (ICC-ES, 2022; 2023a). In June 2023, ICON became the second 3DCP technology company to have ESR-4652 published in compliance with AC509.

In addition to the ICC, UL Solutions (n.d.) developed standard UL 3401 "to evaluate and confirm that a fabricator's 3D printing equipment, material, and fabrication process consistently produces building elements that maintain the same integrity as the initially tested samples." This standard was incorporated into the 2021 International Residential Code as an appendix that local building code departments can adopt to demonstrate code compliance.

Generally, the AC509 and UL 3401 attempt to ensure the same high-quality and consistent performance results—through some specification the building code recognizes. 3DCP technology companies may also develop their own test protocols for independent third-party laboratory implementation along with a test report. This approach may require more interaction with the local building code official, because it may not be codified by AC509 or UL 3401. Apis Cor developed their own test protocol to demonstrate equivalence with concrete masonry unit construction and engaged independent laboratories to issue a test report (NFPA, 2020).

3DCP technology companies must be prepared to demonstrate building code compliance and assist builders and developers with navigating the local building code process through option two or three or a combination of both. The authors believe that 3DCP technology will need to be defined and standardized before it will be formally incorporated into the building code. The standardization of construction practices using 3DCP technology might be premature given the rapid development and reformulation taking place in the industry, but ultimately, standardization and reliability are very important steps when ensuring the performance and safety of any building product. This step can take many years, especially when the technology is new, and the "know-how" is proprietary.

All 3DCP technology companies should actively engage in the code and standard development processes to ensure that regulators and model code developers understand the technology and how the technology is developing next. 3DCP technology companies should develop voluntary performance specifications that allow innovation to continue, while both educating the public on what good performing products look like and what is unacceptable.[14] Check the ICC-ES website for companies that claim to have an ESR in compliance with AC509.

[14] See exhibit A-2 for companies claiming compliance with UL 3401.

Characterizing the Cost of Construction

The cost of construction using three-dimensional concrete printing (3DCP) technology cannot be accurately determined for three reasons.

1. To date, fewer than 20 3DCP buildings have been built and occupied in the United States, and each completed building was constructed using different types of 3DCP technology and various material formulations.
2. Labor and material requirements vary based on the size and complexity of the building and the 3DCP technology used. Standardized construction methods are lacking.
3. Some of the reported savings, or benefits, are difficult to quantify without cost data, which are not available from 3DCP technology companies. The data are confidential.

This report recommends benchmarking the cost of the 3DCP home against a comparable-sized concrete masonry unit (CMU)-built home. The rationale for this approach is simple. Both building types should perform similarly in terms of building performance, and the benefits in terms of resilience against fire, termites, and high-wind storm hazards should be similar. The cost of a CMU-built home can be estimated using RSMeans construction cost data and other commonly used construction cost resources. In addition, the cost will vary based on location, which can also be easily considered.

If a developer considers hiring a vertically integrated 3DCP technology company to build 3DCP homes, the comparison with a CMU-built structure will be straight forward, because the total cost of one house type can be compared directly with the other—such as, are the costs the same, less, or more? If a builder considers hiring a 3DCP subcontractor to replace a CMU subcontractor, the cost comparison can be straightforward, but how does this change affect the other trades? Do the changes in performing the construction add or reduce costs (or construction time) to the other trades? The builder must not just consider the cost of changing subcontractors but also the changes to how the building is built. If a builder considers purchasing 3DCP technology, calculating construction cost is more complicated, and the ideal condition for making the investment must be weighed against the learning curve and the capital investment.

When considering the construction cost, it may not be reasonable to expect that any new technology will be immediately cost-competitive with a mature building material or construction method. In other industries, especially high technology or computers, the price is expected to be initially high and then gradually reduce overtime. Integrating robotics into construction on the jobsite is unique and may require a more indepth study to determine what is reasonable to expect and if the increased cost and value proposition can be justified due to construction labor shortages.

Labor Requirements

Labor requirements when using three-dimensional concrete printing (3DCP) technology may vary greatly for three reasons.

1. The labor expertise required to operate 3DCP technology is different from the conventional construction labor that it seeks to replace, resulting in two needs: (1) workforce development to create the labor required to operate 3DCP technology and (2) retraining of existing construction workers who will be impacted negatively (if 3DCP technology is widely adopted). Can current labor be retrained to operate 3DCP technology?
2. 3DCP labor requirements vary with the technology being used and the size of the structure. The team observed a number of different operators on jobsites when building a single-family home compared with a multifamily home.
3. Most 3DCP technology companies claim that fewer people are needed to operate the 3DCP printers compared with the number of masons or framers needed for conventional construction. This claim may be true, but if the unit cost is higher for a 3DCP operators compared with masons or framers, the overall labor cost might increase.

The authors' market research findings show that approximately 70 percent of surveyed builders preferred to hire a 3DCP subcontractor to deliver a printed exterior wall. This finding means that existing masons and framers would need to see value in making the investment in the technology and retraining employees to operate the robotics, or new 3DCP subcontractors would need to displace conventional construction labor. If the $800,000 investment in 3DCP technology is a barrier for a large general contractor, it will likely be harder for subcontractors to make the investment.

The Home Builders Institute estimated that the shortage in housing inventory will continue due to the "lack of skilled construction labor [which] is a key limiting factor to expanding home construction and improving housing inventory and affordability" (HBI, 2023). In April 2023, the Hass School of Business at the University of California Berkeley published a paper that "provides novel evidence on a less-explored channel affecting housing supply: shortages of construction labor." They argue that immigration policy has negatively affected construction sector employment. It has led to "reduced housing supply that is associated with increased home prices" (Howard, Wang, Zhang, 2023).

These labor shortages have been observed in carpentry and framing, and if 3DCP technology can add labor capacity without eliminating any existing construction jobs, it might then help solve the labor shortage problem in housing, especially if it can be integrated without disrupting other labor types and using standard existing building products.

How to Integrate 3DCP Technology

The team observed three-dimensional concrete printing (3DCP) construction in the field for single-family and multifamily buildings.[15,16] In addition, the team procured a 3DCP test wall from Black Buffalo to conduct physical testing and hands-on evaluations of various construction practices. The technical evaluation (1) identified the range of construction practices that currently exists when installing 3DCP walls with other traditional building products, (2) recommended areas that would benefit from standardization, and (3) provided questions that builders ask when engaging 3DCP technology companies.

The team visited ICON's single-family home during construction (exhibit 13). For this house, it is important to note that the first story was printed using ICON's gantry-style Vulcan printer, and the second story was constructed using conventional stick frame construction techniques.[17] This podium-style construction approach is typical in low- or mid-rise construction when mixed-use buildings are constructed. At the time of publication, the Vulcan printer had a height limitation. As a result, a two-story structure could not be printed.

Exhibit 13. ICON Technology's Single-Family Home in Austin, Texas

ICON 3D Printed House Under Construction. Photo credit: Home Innovation Research Labs (2021).

The team visited PERI's multifamily apartment building during construction (exhibit 14). For this apartment building, the entire three-story building is printed using COBOD's gantry-style BOD2 gantry printer. The 3DCP techniques are similar, but the scale is different in terms of reinforcement and size of the structural members. Builders and developers must note these

[15] Home Innovation visited ICON's single-family building in Austin, Texas: https://www.iconbuild.com/.
[16] Home Innovation visited PERI's multifamily building in Houston, Texas: https://www.peri3dconstruction.com/en.
[17] The Vulcan Construction System has a maximum 10.5-foot print height: https://www.iconbuild.com/technology.

differences when determining which technology to use, and the technology selection will affect a building's design and specifications.

Exhibit 14. PERI 3D Construction's Multifamily Apartment Building in Houston, Texas

Multifamily Building Under Construction. Photo credit: Home Innovation Research Labs (2022).

The technical evaluation focuses on the exterior load-bearing wall, because it is the primary part of the building constructed using 3DCP technology. Observed and evaluated construction practices included (1) foundation to wall construction, (2) wall insulation options, (3) window installation, (4) door installation, (5) plumbing and electrical installation, (6) wall-to-floor construction (7) wall-to-roof construction, and (8) finishing options for interior and exterior walls.

Builders, developers, and those interested in using 3DCP technology must note that some construction methods and practices will change over time. As a result, the team expects some of the construction details in this document to become outdated and superseded by new innovations currently under development. Hence, the following technical evaluation is a snapshot in time that reflects the current technology at the time of publication.

Methodology for Technical Evaluation of 3DCP Technology

The authors used the following four-step process to evaluate the 3DCP construction processes and, when possible, consulted with more than one 3DCP technology company on all construction practices.

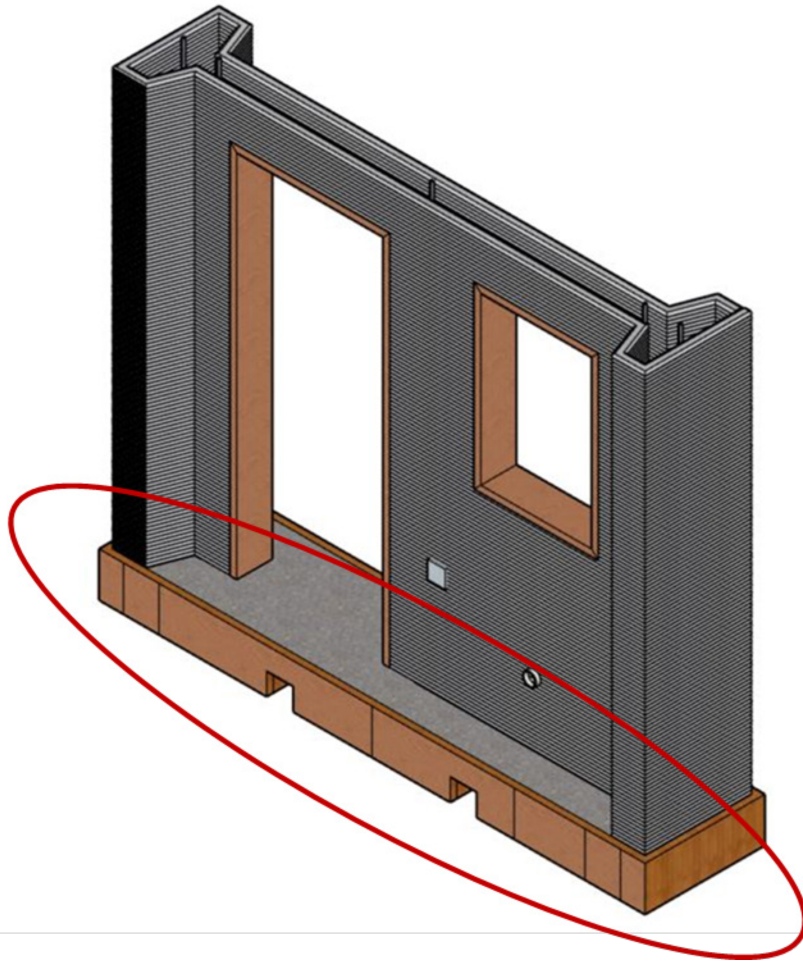
1. The team visited two sites to observe the construction of a single-family home and multifamily building.
2. The team conducted American Society for Testing and Materials E331 testing on windows and doors installed in a prototype 3DCP wall.

3. The team hired contractors to install conventional building products onto the prototype 3DCP wall procured from Black Buffalo to observe any issues that may affect the quality of installation (exhibit 15). The team also added an illustrated version, shown in exhibit 16, to highlight the different portions of the test wall.
4. The team discussed the technical findings with the 3DCP technology companies and an advisory group comprised of 25 or more industry stakeholders. The team asked the advisory group to discuss the potential implications of widespread adoption of 3DCP technology on the building industry and what would be needed to realize the best outcome.

Exhibit 15. Black Buffalo 3D Construction's Printed Test Wall

3D Printed Test Wall. Photo credit: Home Innovation Research Labs (2022).

Exhibit 16. Illustrated Foundation Connections for Printed Test Wall



Source: Home Innovation Research Labs

Foundation-to-Wall Construction

Black Buffalo constructed a typical concrete foundation footer to demonstrate how a 3DCP wall should be printed, structurally tied to the foundation, and then structurally reinforced with vertical and horizontal rebar. The techniques were similar to those illustrated in the *CMU Annotated Design and Construction Details for Masonry Design Manual* published by the National Concrete Masonry Association.

The team observed the following steps. The foundation component was poured using standard concrete material, not the special 3DCP material concrete material (exhibit 17). Then, the rebar locations were predrilled into the foundation, and the exterior wall geometry was printed onto the footer. Both vertical and horizontal rebar were installed (exhibit 18).

Exhibit 17. Poured Foundation

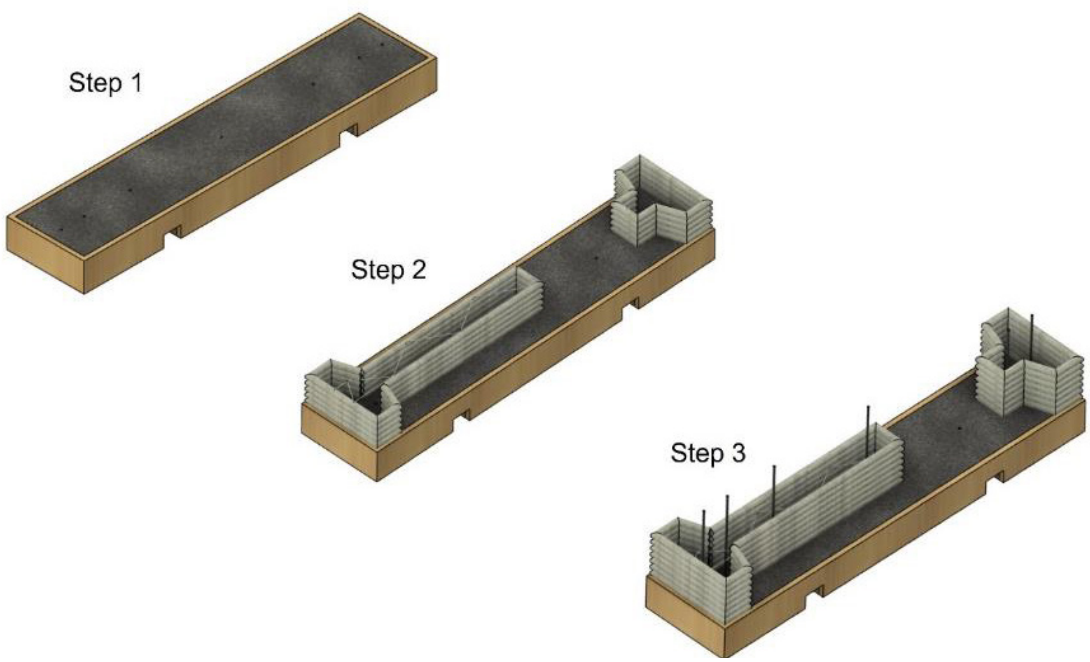
Foundation.
Photo credit: Home Innovation Research Labs (2022).

Exhibit 18. Reinforced Test Wall

Reinforcement Installed.
Photo credit: Home Innovation Research Labs (2022).

During the printing process, the team observed some pump flow issues that resulted in material surges creating a few nonuniformed layers of extrudate (seen on the edge of the wall in exhibit 18). This issue was determined to be structurally acceptable after the wall cured, but aesthetically, it could be a problem if the finish was supposed to be natural. Exhibit 19 illustrates the steps.

Exhibit 19. Foundation-to-Wall Construction Illustrated Steps



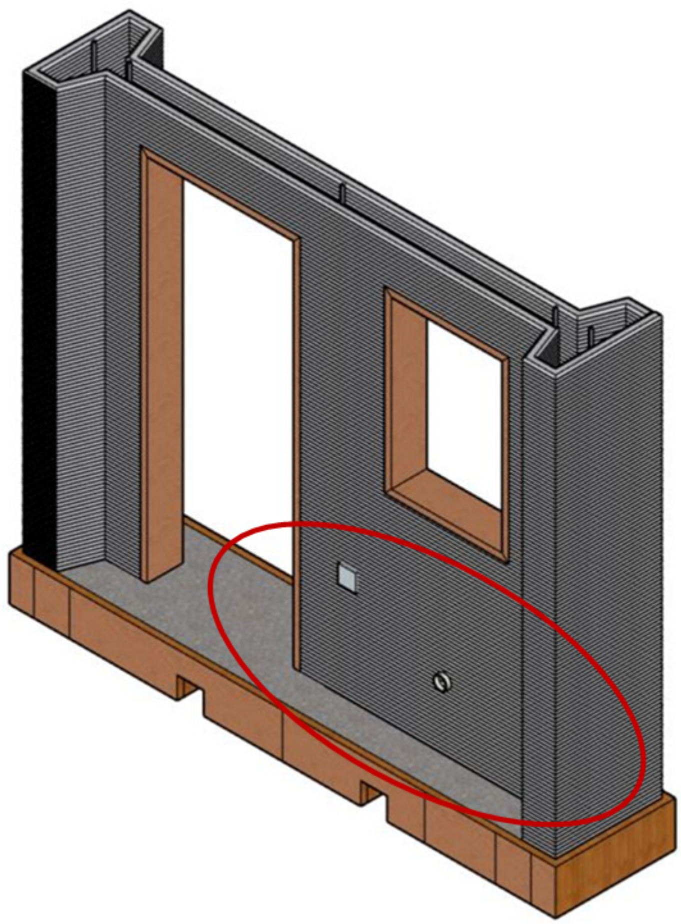
Source: Home Innovation Research Labs

Wall Insulation Options

For the prototype 3DCP test wall, portions of the wall were filled with printed concrete extrudate to increase its load-bearing structural capacity and further secure the rebar and reinforcement materials. Nonetheless, foam insulation can be added inside the internal cavity of the wall, or rigid foam board insulation can be added to the interior or exterior surfaces of the printed wall. In addition, a triple-bead wall could be printed, with one cavity filled with cementitious mortar and the other left open for installing mechanical, electrical, and plumbing services or insulation.

The team was not present to observe installing wall insulation during any of the site visits for 3DCP single-family or multifamily buildings. Instead, the team installed the interior and exterior rigid foam insulation on the interior and exterior of the printed test wall for the section of wall illustrated in the circled area of exhibit 20.

Exhibit 20. Illustrated Rigid Foam Insulation Area for Printed Wall



Source: Home Innovation Research Labs

The team installed the rigid insulation foam board on the corrugated area of the wall, circled in red, to demonstrate how the insulation would attach to the natural unfinished corrugated concrete without a stucco or a flat finish. Exhibit 21 shows the corrugated surface, and exhibit 22 shows the Extruded Polystyrene (XPS) Rigid Foam installed.

Exhibit 21. Corrugated Concrete Surface

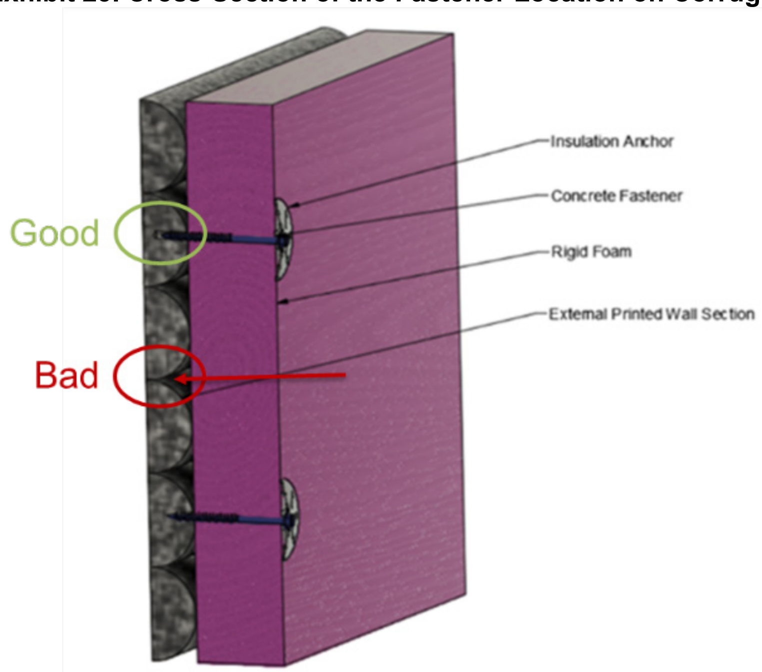
Close-Up View Corrugation.
Photo credit: Home Innovation Research Labs (2022).

Exhibit 22. Extruded Polystyrene Insulation

Exterior Wal Insulation.
Photo credit: Home Innovation Research Labs (2022).

The irregular surface of the printed wall in exhibit 21 damaged the insulation board in exhibit 22 when the fastener was between the corrugated features. The damage to the rigid insulation was crushing the board due to overdriving the fastener. To prevent this damage, the fasteners had to be on the top center of the corrugated features, such that the fastener fully supports the foam (exhibit 23). After locating the top of the corrugated feature, the team marked it with a pen to transfer the location to the foam board.

Exhibit 23. Cross-Section of the Fastener Location on Corrugated Surface



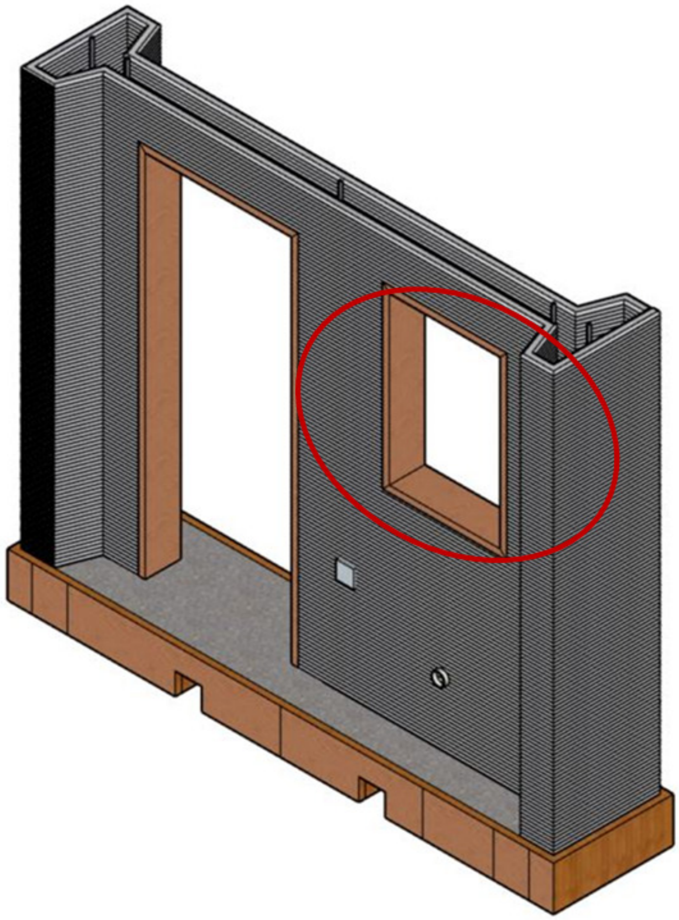
Source: Home Innovation Research Labs

The team also eliminated the corrugated surface by filling in the feature with stucco or concrete material, which made the surface flat and even. Any secondary finish on top of the corrugated wall would likely increase the construction cost, but it may be unavoidable when installing insulation or an exterior cladding product.

Window Design and Installation

The window design and installation are critical to the building envelope performance. The exterior face of the wall was evaluated for water penetration at the areas surrounding the window opening (the area circled in red in exhibit 24). The test was conducted in accordance with the American Society for Testing and Materials (ASTM) E331 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.

Exhibit 24. Illustrated Test Wall With Window Location



Source: Home Innovation Research Labs

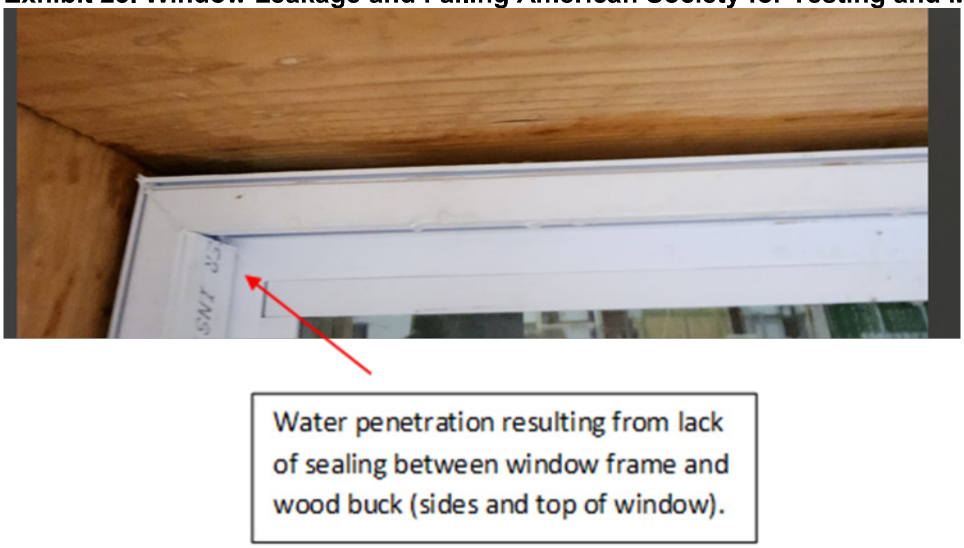
The 3DCP test wall specimen included a single operable window, which was not independently or randomly selected for testing by the team. Instead, Black Buffalo purchased and installed the window as an integral part of the 3DCP test wall, which was transported from Newark, New Jersey, to Upper Marlboro, Maryland. On receipt, the test wall was not visibly damaged or tampered with prior to shipment. During preparation of the test wall, Black Buffalo performed additional concrete patchwork to fill some concrete voids created during the printing process, but some portions of the wall surface were left with the typical corrugated surface and minor irregularities one would see after printing a 3DCP structure. The concrete patchwork to the test wall was done at Black Buffalo's plant—after printing but before shipping. The team received the specimen in April 2022 and completed all testing on October 21, 2022.

The team conducted, observed, and documented testing. The test method and equipment used were in accordance with the ASTM E331 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.

The testing chamber was calibrated in accordance with section 9 of ASTM E331. The water-spray system was calibrated at both upper corners and at the quarter point of the horizontal center line (of the spray system) for a combined flow rate of 1.87, 1.75, and 1.29 liters per minute in the top left, top right, and center, respectively. The spray hose was offset by 18 inches to account for the space between the chamber and exterior face of the specimen.

Water penetration became visible after 10 minutes of testing. Water penetration was evident at gaps around the window and concrete (exhibit 25).

Exhibit 25. Window Leakage and Failing American Society for Testing and Materials E331



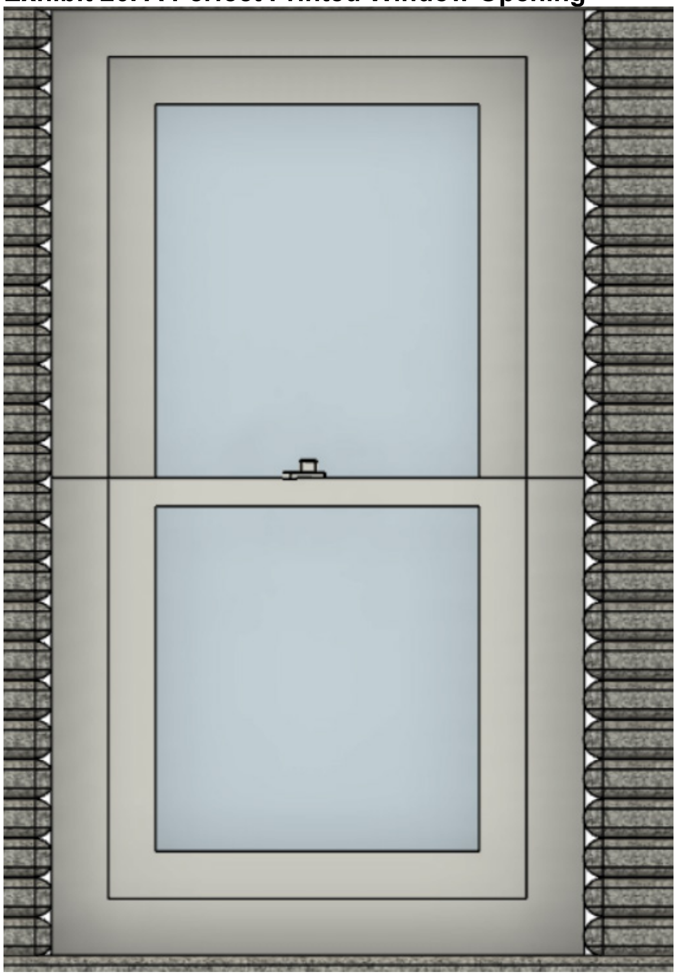
Close-Up post-test window inspection. Photo credit: Home Innovation Research Labs (2022).

The team evaluated the mode of failure and determined that the flashing or sealing between the wood frame and the window was not adequate. Because the test wall was shipped from Newark, New Jersey (its print location), to the Home Innovation laboratory in Upper Marlboro, Maryland, some invisible microcracking, occurring at the seals and flashing due to vibrations or movement during transit, is a possibility.

Nonetheless, two other causes of the water leakage are possible. First, the quality of the 3D print around the window opening was poor, and the effort to seal and flash the window opening was inadequate. Second, the curved wall feature that the printer created requires a custom window and flashing product, because the curved corrugated features create too many voids to fill adequately.

A perfectly 3D printed window opening will have openings where the window frame and printed window opening meet due to the corrugated surface of the 3DCP wall (exhibit 26). These openings can be sealed with (1) a custom window and flashing product, (2) by using a sealing product to fill all openings, or (3) by applying concrete patchwork material to fill the openings and make the surface flat such that the window can be flashed and sealed like a wood-framed window opening.

Exhibit 26. A Perfect Printed Window Opening



Source: Home Innovation Research Labs

A wood buck for blocking the window opening can provide the window with a flat surface for installation, but the openings the 3DCP corrugated surface caused will still need to be sealed, but now against the wood buck instead of the window frame. The team suspects that the window did not pass ASTM E331 because of poor sealing of these openings, which are due to the printer's nozzle design.

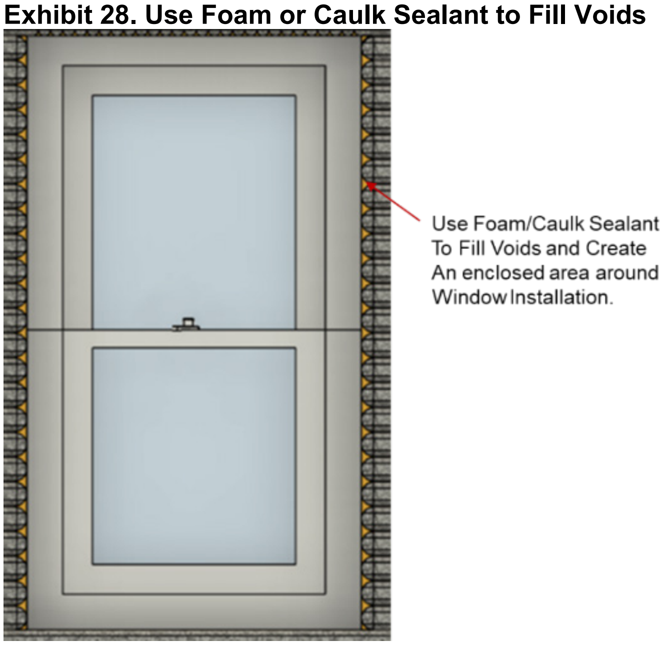
One solution is to use concrete material to patch and fill the voids in the window jambs before installing the window (exhibit 27). This solution requires some secondary concrete work in addition to the original print, but now a standard window can be installed with typical flashing and sealing details. Some 3DCP technology companies have explored new nozzle designs to eliminate gaps around windows.

Exhibit 27. Use Concrete to Patch and Fill Voids

Source: Home Innovation Research Labs

The most common solution observed was installing a custom-type window, with a special manufacturer-designed flashing system. Then, foam caulk sealant is used to fill the remaining voids. Exhibit 28 shows the foam caulk sealant as orange material.

Exhibit 28. Use Foam or Caulk Sealant to Fill Voids

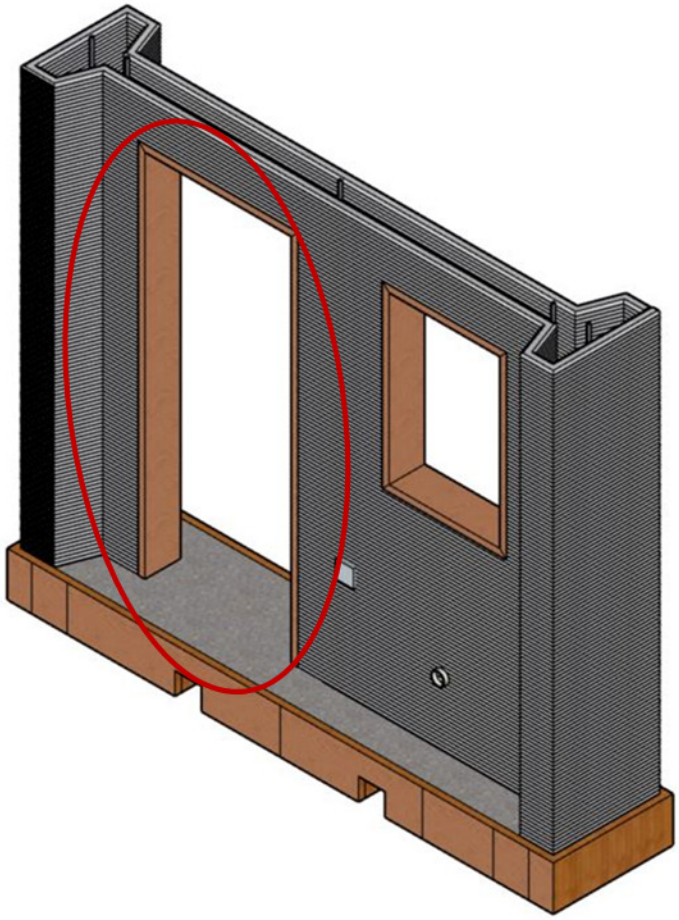


Source: Home Innovation Research Labs

Door Design and Installation

The door design and installation are also critical to the performance of the building envelope. The exterior face of the wall was evaluated for water penetration at the areas surrounding the window opening (the area circled in red exhibit 29). The test was conducted in accordance with ASTM E331 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.

Exhibit 29. Illustrated Test Wall With Door Location



Source: Home Innovation Research Labs

The 3DCP test wall specimen included a single operable door, which was not independently or randomly selected for testing by the team. Instead, Black Buffalo purchased and installed the door as an integral part of the 3DCP test wall, which was transported from Newark, New Jersey, to Upper Marlboro, Maryland. On receipt, the test wall was not visibly damaged or tampered with prior to shipment. During preparation of the test wall, Black Buffalo performed additional concrete patchwork to fill some concrete voids created during the printing process, but some portions of the wall surface were left with the typical corrugated surface and minor irregularities one would see after printing a 3DCP structure. The concrete patchwork was done to the test wall at Black Buffalo's plant—after printing but before shipping. The team received the specimen in April 2022 and completed all testing on October 21, 2022, during the same time as testing the window.

The team conducted, observed, and documented testing. The test method and equipment used were in accordance with ASTM E331 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.

The testing chamber was calibrated in accordance with section 9 of ASTM E331. The water-spray system was calibrated at both upper corners and at the quarter point of the horizontal center line (of the spray system) for a combined flow rate of 1.87, 1.75, and 1.29 liters per minute in the top left, top right, and center, respectively. The spray hose was offset by 18 inches to account for the space between the chamber and the specimen's exterior face. The door was mounted to a wood buck by a series of nine screws total—two 1.75-inch screws directly into the buck and seven 2-inch screws holding the hinge into frame and buck—along the sides of the door (exhibit 30).

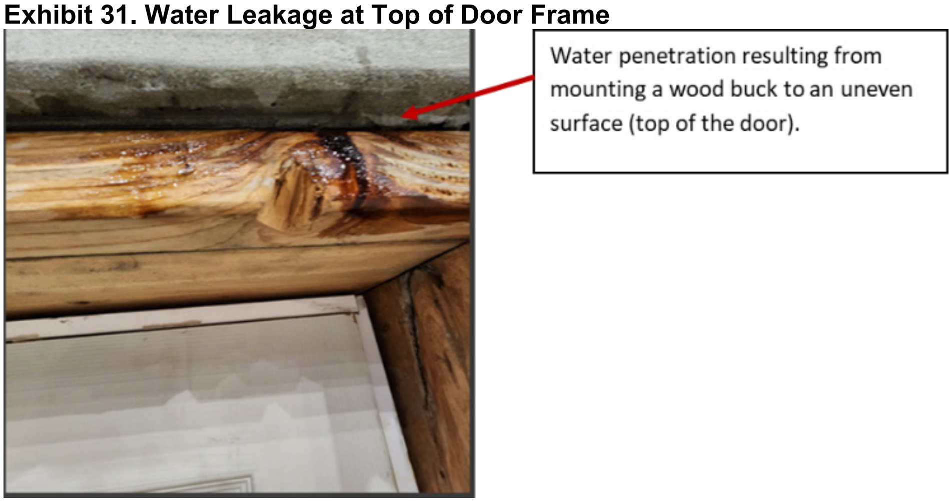
Exhibit 30. Door Installation Details

Close-Up of Door Fastener Types Used. Photo credit: Home Innovation Research Labs (2022).

In preparation for the test, the team opened, closed, and locked the door for a total of five cycles. The locking mechanism could prevent the door from opening while engaged. The team applied expanding foam tape to seal the gap at the door sill for testing.

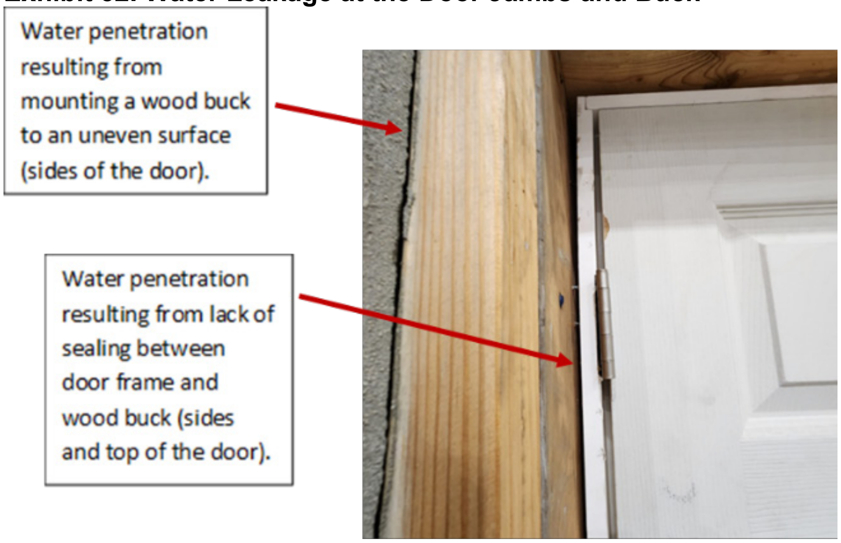
Water penetration became visible after 10 minutes of testing. Water penetration was evident at the gaps around the door bucks and concrete, around the installed door, and at the bottom of the door (exhibits 31 and 32).

Exhibit 31. Water Leakage at Top of Door Frame



Close-Up of Door Inspection Leak. Photo credit: Home Innovation Research Labs (2022).

Exhibit 32. Water Leakage at the Door Jambs and Buck



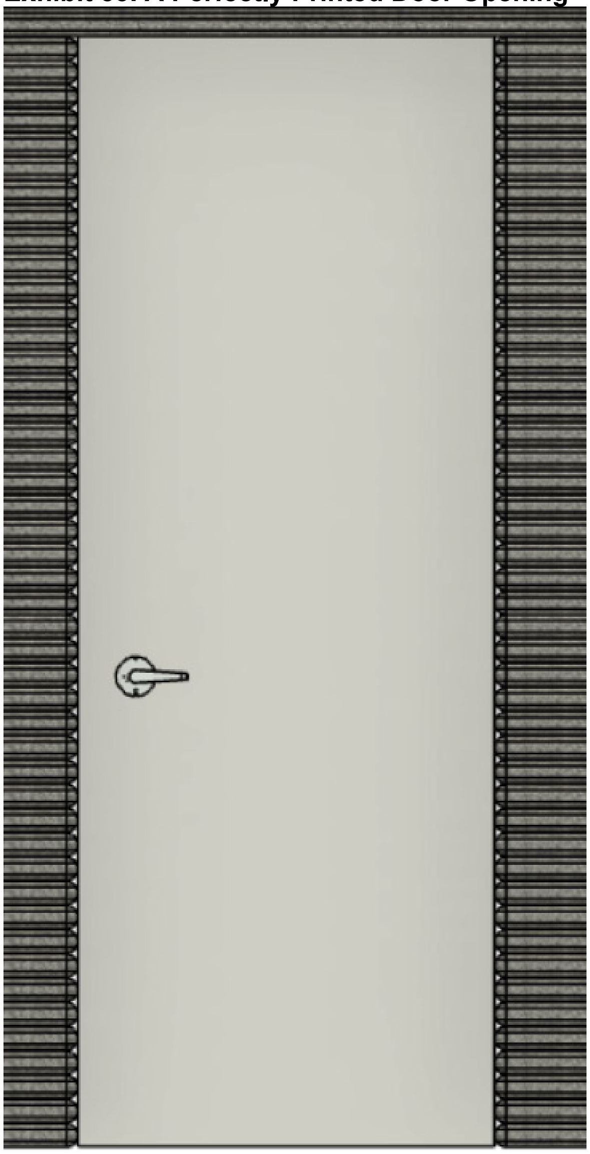
Close-Up of Wall Jamb Leaks. Photo credit: Home Innovation Research Labs (2022).

The team evaluated the mode of failure and determined that the problem with the door was like the problem with the window in that flashing or sealing between the door, wood buck, and 3DCP wall jambs were not adequate. It is suspected that some invisible microcracking could have occurred at the seals and flashing due to vibrations or movement during transit.

Nonetheless, two other causes of the water leakage are possible—similar to the window. First, the quality of the 3D print around the door opening was poor, and the effort to seal and flash the door opening was inadequate. Second, the curved wall feature that the printer created requires special flashing and sealing techniques, because the curved corrugated features create too many voids to fill adequately. Again, like the windows, the team recommends that the door opening be finished in a manner that eliminates gaps and openings.

A perfectly printed door opening will have gaps between the door frame and door jamb due to the corrugated surface of the 3DCP wall (exhibit 33). The remedy is similar to what is prescribed for window openings. These openings can be sealed with (1) custom designed doors and flashing, (2) by using a sealing product to fill all openings, or (3) by applying concrete patchwork material to fill the openings and make the surface flat such that the door can be installed like any other standard door product.

Exhibit 33. A Perfectly Printed Door Opening

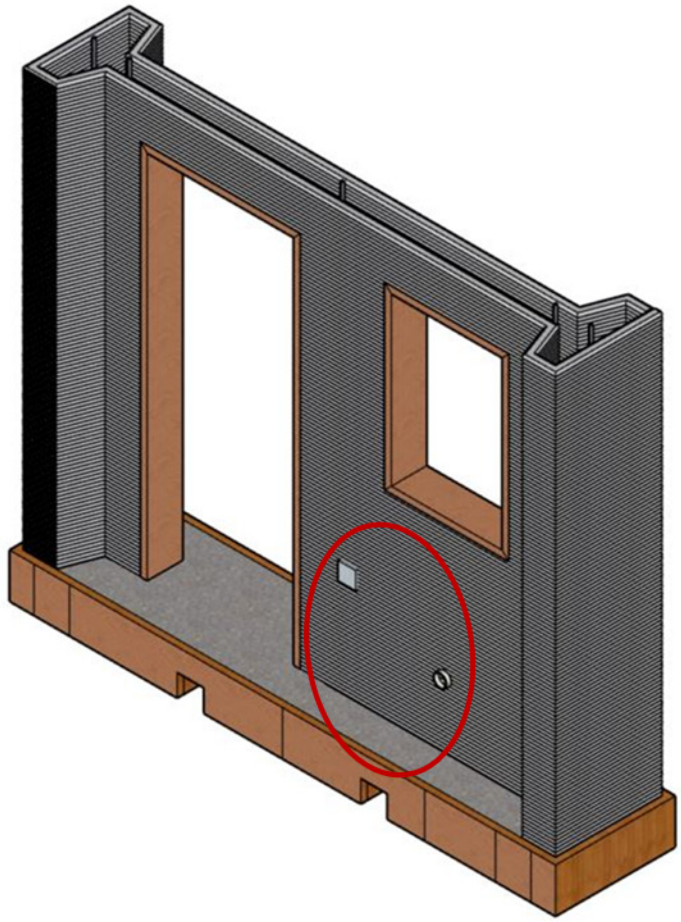


Source: Home Innovation Research Labs

Utility Design and Installations

3DCP technology companies have three options when considering how utilities must be installed or integrated into 3DCP walls: (1) print the utility features within the 3DCP wall cavity, (2) cut out openings before the printed wall cures, or (3) install the utilities directly on the surface of the 3DCP wall or a finished interior wall. In either case, it is a change for conventional stick frame builders, because once the wood sheathing and 2x4 framing are installed, the interior wall remains open until plumbing, electrical, ventilation, insulation, and other services are installed. Because 3DCP walls are printed fully closed, some work that is typically done later in the construction process must be done earlier, especially if a builder intends to add certain features into the 3DCP wall. Exhibit 34 shows both electrical and plumbing utility locations.

Exhibit 34. Illustrated Test Wall for Utility Locations



Source: Home Innovation Research Labs

Using 3DCP technology will require changes to the overall construction process. To optimize the schedule and save time, electricians will need to install receptacles into the 3DCP wall much sooner than they would in convention stick frame walls. To save time, the 3DCP technology company may ask others to do some of the electrical work, such as placing electrical receptacles within the 3DCP wall. However, depending on the building code and licensing requirements, that work may only be allowed by a licensed electrician. For new construction, a licensed plumber is typically needed in most states, and they will not allow nonplumbers to do parts of their job in an effort to expedite the 3DCP wall installation.

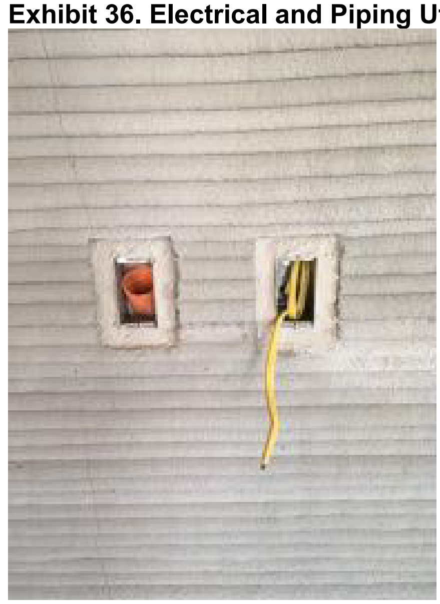
To maximize the potential time savings in the construction process, 3DCP subcontractors will not have the ability to influence or change how other subcontractors, such as plumbers and electricians, do their jobs. To fully implement the benefits of 3DCP technology, the general contractor or project manager must be willing to change the sequence and timing of when and how work gets done. When considering how best to design and install utilities, both plumbers and electricians must be part of the process. In cases with printing only the exterior wall, plumbing service may not be in the wall or penetrating through the wall if the plumbing service runs underground. Hence, the plumber and 3DCP subcontractor may not need to discuss plumbing needs. However, every house has electrical service within the exterior walls, and it will be critical to involve electricians in the design phase and in actually installing electrical utilities.

The team observed utility features being placed into the test wall during printing. In the case of the electrical receptacle, the team noticed that it was placed into the wall cavity after printing the wall section by removing a portion of the exterior printed layer and installing a conduit to the receptacle from within the printed wall cavity. This type of installation is not common for taller concrete masonry unit (CMU) buildings, because the additional work required to run wire and receptacles within concealed walls on multiple floors can cost more than a surface mount installation. Exhibit 35 shows the electrical receptacle Black Buffalo installed. In addition, exhibit 36 shows utilities printed inside the 3DCP wall by ICON during the site visit to observe construction of their single-family home in Austin, Texas.

Exhibit 35. Electrical Utility

3D Printed Test Wall with Electrical Receptacle. Photo credit: Home Innovation Research Labs (2022).

Exhibit 36. Electrical and Piping Utilities



3D Printed Wall with Close Up of Utilities. Photo credit: Home Innovation Research Labs (2022).

The team and subcontractors installed plumbing supply lines and electrical conduit on the exterior and interior surfaces of the test wall. Although installing utilities within the 3DCP walls may be preferred, this evaluation aimed to determine if surface installations were difficult and under what circumstances do they work best.

Exhibits 37, 38, and 39 show the installation of a pipe through the wall of the 3DCP wall using typical construction tools and equipment. The contractor found the scratch coat or patching concrete material that was applied to the test wall was durable enough to allow holes to be drilled through the wall without damaging the surface.

Exhibit 37. Drilling Through Printed Wall to Install Plumbing Service Line

Close-Up of Drilling for Plumbing. Photo credit: Home Innovation Research Labs (2022).

Exhibit 38. Drilled Hole for Plumbing

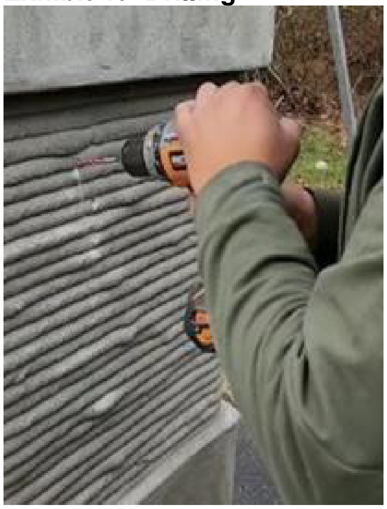
Prep of Wall for Plumbing Installation
Photo credit: Home Innovation Research Labs (2022).

Exhibit 39. Pipe Installed

Plumbing Installation Complete.
Photo credit: Home Innovation Research Labs (2022).

The subcontractor installed electrical conduits on the rough corrugated portion of the 3DCP test wall. In addition, they installed similar electrical conduits on the flat surface of the 3DCP wall that had been treated with a scratch coat or concrete patch material. In all cases, installation was similar to CMU buildings, and the work was completed without issue. Exhibits 40, 41, and 42 show the corrugated wall installation, and exhibits 43, 44, 45 illustrate the smooth wall finish.

Exhibit 40. Drilling



Mounting details. Photo credit: Home Innovation Research Labs (2022).

Exhibit 41. Front

Photo credit: Home Innovation Research Labs (2022).

Exhibit 42. Side

Photo credit: Home Innovation Research Labs (2022).

Exhibit 43. Preparing Wall

Mounting on Flat Wall Finish. Photo credit: Home Innovation Research Labs (2022).

Exhibit 44. Front View

Receptacle installed on Flat Wall. Photo credit: Home Innovation Research Labs (2022).

Exhibit 45. Side View

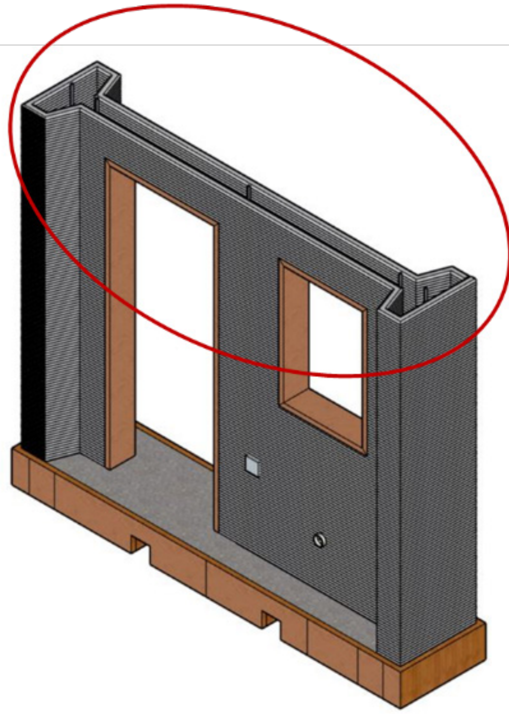
Notice no space between Wall and Receptacle. Photo credit: Home Innovation Research Labs (2022).

The contractor also installed a surface mount electrical receptacle on the interior drywall to demonstrate more design and installation options.

Wall-to-Floor and Wall-to-Roof Connections

The team did not observe second floor or roofing installations on the buildings during 3DCP construction site visits. Nonetheless, the team and subcontractor were able to evaluate different options for both floor and roof connection types. Exhibit 46 illustrates the area of the test wall evaluated.

Exhibit 46. Illustrated Test Wall for Floor and Roof Locations



Source: Home Innovation Research Labs

The top of the 3DCP test wall is designed to install either a joist floor system or roofing truss system. The team decided to evaluate both systems, starting with the floor, because Black Buffalo developed a custom joist hanger for the upper floor construction. The evaluation was not a test of the joist hanger's strength or to quantify the structural performance; instead the team was interested in determining whether the joist hangers can be used with 3DCP technology.

Exhibits 47 and 48 show the custom joist hanger developed by Black Buffalo 3D. The installation procedure was similar to a typical CMU application. The team noticed that at the top of the test wall, the scratch coat finish (or patching concrete material) was more brittle than the surface finish on the rest of the wall sections. The finished material cracked due to drilling and during installing concrete screws for the custom joist hangers. The standard joist hangers in exhibits 49 and 50 are available from commercial product manufacturers and performed well in terms of installation ease and are readily available.

Exhibit 47. Black Buffalo 3D Construction's Custom Joist Hanger

Custom Installation of Joist Hanger. Photo credit: Home Innovation Research Labs (2022).

Exhibit 48.
Custom Joist Hanger

Proprietary Joist Hanger
Photo Credit
Home Innovation Research Labs
(2022)

Exhibit 49.
Type 1 Joist Hanger

Standard Joist Hanger.
Photo credit:
Home Innovation Research Labs
(2022).

Exhibit 50.
Type 2 Joist Hanger

Top Mounted Joist Hanger.
Photo credit:
Home Innovation Research
Labs (2022).

After completing the joist hanger evaluation, the team started evaluating the roof truss. The roof connection site was right above the door frame. The 3DCP test wall was fitted with metal framing and lentil. The roofing system was installed in accordance with *ICC 403.12 Roof Systems*, showing two different anchorage options for direct-bearing connections.

One option used a ½-inch wedge anchor to install a sill plate after the print had fully cured. The other option used J anchors set perpendicular to the top surface and suspended while concrete, or an equivalent strength adhesive, was poured and settled to fasten the anchors, representative of a during-print and precure installation.

After installing the J anchors, additional concrete and adhesive were added to completely fill the opening and allowed to settle. Once settled, a sill gasket was placed over the wall to cover the entire thickness, and a pressure treated and predrilled 2x12 was trimmed to the thickness of the wall and inserted (exhibit 51). Exhibits 52 and 53 show the partial roof truss.

Exhibit 51. Roof-to-Wall Cross-Section

Close-Up of Roof to Wall Connection.
Photo credit: Home Innovation Research Labs (2022).

Exhibit 52. Roof Truss-to-Wall Connection

Roof Structure Mounting Detail.
Photo credit: Home Innovation Research Labs (2022).

Exhibit 53. Partial Roof Truss and Top Plate of Printed Wall

Close Up of Roof Structure Mounting. Photo credit: Home Innovation Research Labs (2022).

Generally, the scratch coat or patching material used on the three-dimensional concrete printed test wall was not as durable as the printed material. The team observed several cracks in the scratch coat during installation.

Finishing Options for Interior and Exterior Walls

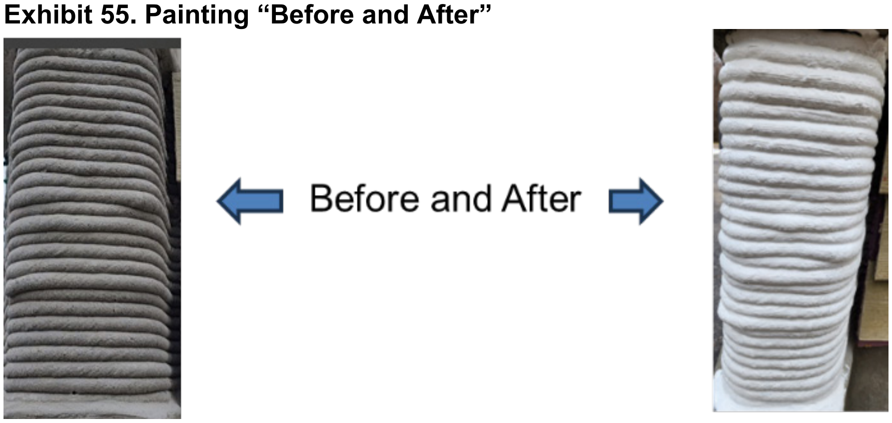
Currently, finishing options for 3DCP buildings are not many beyond a coat of paint. Generally, the leading providers of 3DCP homes promote a natural printed aesthetic with a painted finish, because adding other finishing options—such as stucco, cladding, or drywall—will increase construction costs (exhibit 54). Nonetheless, the power and value of aesthetics cannot be underestimated in the choices that people make when selecting a home to purchase.

Exhibit 54. Typical Interior Wall Finish for Printed Homes

Model 3D Concrete Printed Home Interior in Austin, Texas.
Photo credit: ICON.

The team evaluated the pros and cons of paint as a finishing option, noting that paint does not hide any imperfections on wall surfaces. However, it may make some microcracks less noticeable. Exhibits 55 and 56 highlight the pros and cons of using paint to finish walls.

Exhibit 55. Painting "Before and After"



Painting can protect the surface but not appearance.
Photo credit: Home Innovation Research Labs (2022)

Exhibit 56. Pros and Cons of Elastomeric Paint

ELASTOMETRIC PAINT	
PROS	**CONS**
Offers a wide variety of exterior colors	Requires heavy and multiple coats for coverage
Added protection against water infiltration	Irregularities/imperfections remain visible

The team used the 3DCP test wall to demonstrate what is possible with secondary concrete finishes, such as stucco and concrete topcoats, on printed wall surfaces (exhibits 57, 58, and 59).

Exhibit 57. Natural Finish

Test Wall Under Construction with No Finish.
Photo credit: Black Buffalo 3D (2022).

Exhibit 58. Secondary Finishes

Test Wall with Concrete Surface Finish.
Photo credit: Black Buffalo 3D (2022).

Exhibit 59. Finished Surface With Additional Options

Various Surface Finishes on Test Wall.
Photo credit: Black Buffalo 3D (2022).

Applying secondary concrete finishes as exhibit 57 shows will add labor and material cost to the final construction, but the aesthetic value of doing so may increase the chances that the house is preferred and ultimately sold.

The team installed cladding products on the exterior wall surface and noticed it was difficult to do so without damaging the product and, sometimes, the printed wall surface. The team used wood furring to install cladding products. In the future, the team recommends that 3DCP technology companies develop more options for aesthetic finishes, including nozzle design and secondary surface textures.

The prototype wall was not completely representative of an actual printed wall for a home. In addition, the team was unable to develop or recommend “best practices” from the limited field observations and prototype evaluation.

Key Technical Findings and Recommendations

Three-dimensional concrete printing (3DCP) technology has the potential to become part of the solution to the housing shortage, but only a small number of houses have been constructed to date with this new technology. The technology has not been used enough to establish best practices or standardize construction practices. Nonetheless, technical findings suggest that many of the 3DCP construction practices are similar to concrete masonry unit (CMU) installation methods. As result, builders that use CMU construction techniques may be able to transition to 3DCP technology more easily than stick frame builders.

Conclusions

The team's limited product testing and evaluation could not determine best practices. Instead, observations support the need for industrywide standardization in the areas of robotics, supporting equipment, material formulation, and construction practices to ensure that 3DCP products are consistent and easily integrated into conventional construction. To make the technology widely adopted, the building code must recognize and define it, and industry "know-how" and support must be available and easy to access.

The proprietary nature of 3DCP technology makes it difficult to determine construction and equipment operating costs, including service agreements and specialty materials. The high capital investment costs of 3DCP technology are a barrier to entry for most single-family home builders. Nonetheless, many 3DCP technology companies are willing enter leasing agreements or provide turn-key construction solutions to builders and developers that cannot afford to purchase the equipment. Affordability and ease of use are critical to the success of any new building product—it must solve an existing problem, like labor shortages, to have a benefit beyond cost effectiveness.

Integrating 3DCP technology into conventional stick frame construction will require extensive workforce development for the following reasons.

- The skills required to operate and maintain robotics are different than the skills of the carpenter (for example, framers) and masons that the technology will replace. In fact, fewer employees may be needed to operate robotics, and these new skills may command higher salaries compared with carpenters or masons.
- 3DCP companies understand how to print structures, but many lack an understanding of the homebuilding process and how their technology may change wood-frame construction. Currently, most 3DCP companies see themselves as providers of this new construction technology, not partners with builders or developers. Comprehensive education is needed on the basics of construction and how robotics can improve the process.
- 3DCP will change how homes are built, because coordination and sequencing of existing construction trades, such as plumbers and electricians, will be different when robotics are integrated onto jobsites.

Next Steps

HUD has a long history of facilitating the standardization of new technologies through developing design guides with industry stakeholders. The best example is the creation of the *Design Guide for Residential PEX Water Supply Plumbing Systems* that allowed manufacturers to standardize their plumbing products and installation practices. As a result, housing was made more affordable through the widespread use of cross-linked polyethylene, or PEX, plumbing systems.

The 3DCP construction industry will need similar support from HUD given the fact that they do not have an industry trade association, and most of the concrete material formulations and robotics are proprietary. The National Institute of Standards and Technology has been working with the American Concrete Institute and 3DCP technology companies to standardize both the material formulation, in terms of performance requirements, and robotics. However, HUD is best positioned to assist the industry with standardizing construction practices, which are critical to increasing technology adoption and inclusion in the building code.

In addition, a comprehensive design guide and labor study by an independent organization, which does not have a financial stake in 3DCP technology success, is needed to determine the construction cost of 3DCP technology. Too few houses have been built using 3DCP technology, and the level of expertise is not widespread. As a result, much work is necessary to develop basic knowledge and know-how within the construction industry. During this initial period of new product deployment, more collaboration is needed between builders, developers, and 3DCP technology companies. The authors recommend more research to determine construction costs and labor requirements using time studies, which is an observational research method of determining how long it takes to complete a specific task. This work is easily done once a trade association is established or if multiple 3DCP companies participate using randomized data collected for similarly built structures. Currently, the available data are incomplete and not useful for benchmarking or comparative analysis with common construction practices. A major predictor of the widespread adoption of new building technology is construction cost and ease of implementation.

Appendix

Exhibit A-1. Checklist A: Engaging 3DCP Technology Companies

QUESTIONS TO ASK WHEN ENGAGING 3DCP COMPANIES		
KEY QUESTIONS TO ASK	**☑ WHEN COMPLETED**	**NOTES**
ACESSING 3DCP TECHNOLOGY		
Can the company be contracted for the full or partial construction of the property?		
Can the printer and accompanying equipment be leased or rented?		
Can the printer and accompanying equipment be financed and purchased?		
APPLICABLE BUILDINGS FOR CONSTRUCTION		
Is the printer capable of Single-Family (SF) Residential Construction?		
Is the printer capable of Multifamily (MF) Residential Construction?		
Is the printer capable of Light Commercial Construction?		
CODE COMPLIANCE PATH		
Is there an applicable ICC-ES Report for the printer and construction methods?		
Are there standard alternative means and methods used to demonstrate code compliance?		
Is the print/extrude material tested and qualified as a CMU block equivalent by a third-party accredited institution?		
What level of support is being provided for code approval?		
3DCP REQUIRED LABOR		
How many laborers are required for SF residential construction?		
How many laborers are required for MF residential construction?		
Is there a training provided for laborers?		
How long is the training?		
Is there additional support outside and after training?		
Is trouble-shooting support offered?		
Is there an equipment warranty?		
WALL DESIGN AND CONSTRUCTION GUIDANCE		
Are there plans and details for incorporating the foundation?		
Are there plans and details for incorporating insulation?		
Are there plans and details for incorporating windows?		
Are there plans and details for incorporating doors?		
Are there plans and details for incorporating plumbing?		
Are there plans and details for incorporating the electrical?		
Are there plans and details for incorporating the roof?		

QUESTIONS TO ASK WHEN ENGAGING 3DCP COMPANIES		
KEY QUESTIONS TO ASK	**☑ WHEN COMPLETED**	**NOTES**
INTERIOR FINISHING		
Can the natural printed wall be left as is for final use?		
Can the naturally printed wall be painted for final use?		
Can drywall be installed on printed walls for final use?		
EXTERIOR FINISHING		
Can the natural printed wall be left as is for final use?		
Can the naturally printed wall be painted for final use?		
Can cladding be installed on printed walls for final use?		

3DCP = three-dimensional concrete printing. CMU = concrete masonry unit. ICC-ES = International Code Commission Evaluation Service.

Exhibit A-2. Checklist B: Compliance With UL 3401

CATEGORY	ACTIVITY	Y/N
Building Code Considerations (2021 IRC)	Is the organization responsible for designing 3D-printed buildings, structures and building elements certified in accordance with UL 3401?	
	Are the structural design, construction documents and UL 3401 report of findings submitted to and approved by the Building Official?	
	Are the construction methods, consisting of the manufacturer's production equipment and fabrication process in accordance with UL 3401 report of findings?	
	Are all the additive manufacturing materials identified in the UL 3401 report of findings? Are all the containers of the additive manufacturing materials labeled?	
	Are the ambient temperature and environmental conditions at the jobsite when manufacturing materials are deposited, withing limits specified in the UL 3401 report of findings?	
	Are the maximum number of layers permitted, specified curing time and surface preparation or finishing performed as specified in the UL 3401 report of findings?	
	Is the initial inspection of production equipment, including 3D printer, and the fabrication process performed after the production equipment is located on site and before the building fabrication has begun?	
	Is the inspection conducted by representatives of the approved agency that evaluated the fabrication process for compliance with UL 3401? Did the inspection verify fabrication process, including production equipment, 3D-printing parameters, and additive manufacturing materials, are in accordance with the UL 3401 report of findings and the proprietary information in the UL 3401 detailed report of findings?	
Design and Planning	Does the plan include detailed designs with 3D models and blueprints?	
	Has the optimal location for the printer and concrete mixing equipment been determined during planning phase?	
	Has proper foundation and structural support for the structure been established?	
	Has the printing speed, nozzle size, and layer thickness required for the specific project been determined during planning?	
	Has all the required documents been submitted to approved by the building official?	
Material, Equipment, and Handling	Is the 3D Concrete Printer in good working condition? Has it been inspected and oriented properly?	
	Has the concrete mix, aggregates and admixtures been inspected for quality?	
	Are the pump, hoses, and nozzles of the equipment in accordance with the project requirement?	
	Does the site have power generator or power source to connect the 3D printer and other equipment's?	
	Are there required safety gears including helmets, gloves, and protective goggles?	
Site Preparations	Is the construction area clear of debris, rocks, or uneven surfaces?	
	Does the site have adequate space for 3D printer and other equipment?	
	Have the temporary structures for storing materials, equipment and shelter for workers been set?	
	Does the site have adequate lighting and ventilation?	

CATEGORY	ACTIVITY	Y/N
Fabrication Process, Labor, and Safety Considerations	Are there sufficient skilled labors for operating 3D printers and quality control personnel on site?	
	Is a safety engineer present on site to ensure safe operation of equipment, construction environment and safety equipped workers?	
Post Fabrication	Has the printed structure been inspected for any defects or irregularities?	
	Have the rough edges been trimmed and finished?	
	Have the openings been installed and the gaps around openings sealed?	
	Has the necessary treatments such as sanding or sealing of surfaces been performed?	
	Has the printed structure been cured as prescribed by the additive manufacturer?	
OTHER – BEYOND UL 3401	Do you have Third-Party Verification of 3D Printed Wall Properties?	
	Will you be referencing a published ESR report while evaluating the building design and its properties?	
	Are you able to utilize the Printed Wall as a Structural Element?	
	If no, please provide details of the structural elements and approach to building (for example, post/beam, metal/wood/mass timber/concrete)?	

ESR = evaluation service report. IRC = International Residential Code.

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