Seismic Design Methodology for 3D Printed Concrete Buildings

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Abstract

Designing high-quality, affordable homes using novel technology solutions adopted by the construction industry supports the building of strong, sustainable, and inclusive communities. Three-dimensional (3D) construction printing, or additive construction, has shown the potential to revolutionize the construction industry and the housing market, and by extension, support the U.S. Department of Housing and Urban Development (HUD) strategic plan to increase construction productivity and the production of affordable resilient housing. However, the lack of design methodologies and experimental validations that would enable the developed housing solutions to comply with building codes hinders widespread implementation of this technology. This study proposes a 3D printed concrete (3DPC) building design that adopts a lateral force resisting system composed of reinforced 3DPC walls, making it suitable for low-rise 3DPC housing in seismic regions. This proposed design process adopts the Equivalent Lateral Force (ELF) procedure as a design methodology, and this study sets to determine response modification factors (R-factors) and develop strength design equations for different failure mechanisms, which are crucial elements of the ELF procedure.

The proposed strength design equations are derived by adopting concepts from the design of masonry structures and will be experimentally validated by four different full-scale 3DPC walls under lateral loading to failure. Following experimental validation, the proposed design strategy will become available to the construction industry via relevant documentation to be used for the design of low-rise 3DPC residential and commercial buildings. Funding provided by HUD has been essential to executing this research, which will benefit those in need of affordable housing, thus aligning with some of the primary goals of HUD. This work—and construction 3D printing as a whole new industry—will contribute to transforming the housing market by rapidly providing affordable housing that will be more resilient to natural hazards. Recent studies have shown that more than 3.8 million homes are needed in the United States alone, and construction labor to provide housing is currently in decline.

Introduction

Additive construction, also known as construction 3D printing, has grown rapidly over the past decade. Construction 3D printing can address major challenges of the construction industry, such as high homeownership costs and stagnant or declining productivity through automation that will allow for rapid construction and much lower construction costs. Construction 3D printing can also reduce the environmental impact of construction by drastically reducing construction waste (by 30 to 60 percent; [Labonnote, et al., 2016]), eliminating dust particle pollution (Hager, Golonka, and Putanowicz, 2016) and the need for formwork (El-Sayegh, Romdhane, and Manjikian, 2020), which is usually discarded after being used only three or four times on average.

According to the Rider Levett Bucknall (RLB, 2021) quarterly construction cost report, national construction costs saw their biggest quarter-to-quarter increase in 2021 in more than 20 years. The U.S. national average increase in construction costs from January 2021 to April 2021 was approximately 2.91 percent (11.64 percent annualized). A large portion of that cost increase came from construction labor costs, which typically account for 30 to 50 percent of total project construction costs (Apis Cor, 2021), and those costs are particularly affected by the decline in available construction labor. In fact, according to Rider Levett Bucknall (RLB, 2022), a significant workforce shortage currently hinders the construction industry's ability to increase its construction activity (RLB, 2022). Moreover, Habitat for Humanity (2017) reported that an estimated 1.6 billion people around the world live in inadequate shelter or no shelter, which is attributed to rapid population growth and the construction productivity decline. HUD reported, "On a single night in January 2020, 580,466 people experienced homelessness across the United States" (HUD, 2022). Recent studies have concluded that the United States is experiencing a shortage of more than 3.8 million available homes (Badger and Washington, 2022; Freddie Mac, 2021). To promote homeownership and ensure broad access to affordable housing—one of the strategic goals in the *FY 2022–2026 HUD Strategic Plan* (HUD, 2022)—construction of cheaper housing is needed. Construction 3D printing can help increase productivity via automation while significantly decreasing construction labor needs and creating new, better paying jobs.

Another major issue in the construction industry is the production of significant amounts of construction waste. The U.S. Environmental Protection Agency (EPA) estimates that 230 to 530 million tons of construction and demolition waste are produced each year, which accounts for more than twice the amount of all other municipal solid waste combined (EPA, 2017). Reduction in material use or use of recyclable materials could significantly contribute to reducing construction waste.

Large-scale additive construction methods, such as concrete 3D printing, have the potential to address these major challenges faced by the construction industry. Concrete 3D printing is a sustainable, low-waste construction method that helps to reduce the impact of construction and demolition waste on the planet (Apis Cor, 2021; Greener Ideal Staff, 2021; Well and Anderton, 2021). Previous studies have shown that concrete 3D printing can reduce construction waste by 30 to 60 percent, labor costs by 50 to 80 percent, and production times by 50 to 70 percent (Comminal et al., 2020). Therefore, the automation introduced by concrete 3D printing can significantly increase productivity and reduce labor needs while simultaneously creating upskilled job opportunities (El-Sayegh, Romdhane, and Manjikian, 2020).

Concrete 3D printing currently is spearheaded by construction automation companies that have demonstrated the much shorter construction times that can be achieved compared with more conventional construction methods, such as lightweight wood-frame housing (e.g., up to 9 times faster; Apis Cor, 2021) as well as the potential for much lower construction costs (Kreiger, Kreiger, and Case, 2019; Schuldt et al., 2021; Tobi et al., 2018). However, widespread implementation of this technology—which could widely benefit the public via more resilient, more rapidly built, and cheaper housing—is hindered by the following:

- Lack of design methodologies for 3DPC elements.
- Lack of accepted structural designs for 3DPC elements and structures.
- Lack of understanding of the response of 3DPC elements—and, by extension, 3DPC structures—under loads, such as seismic loads, which are present in most parts of the country.

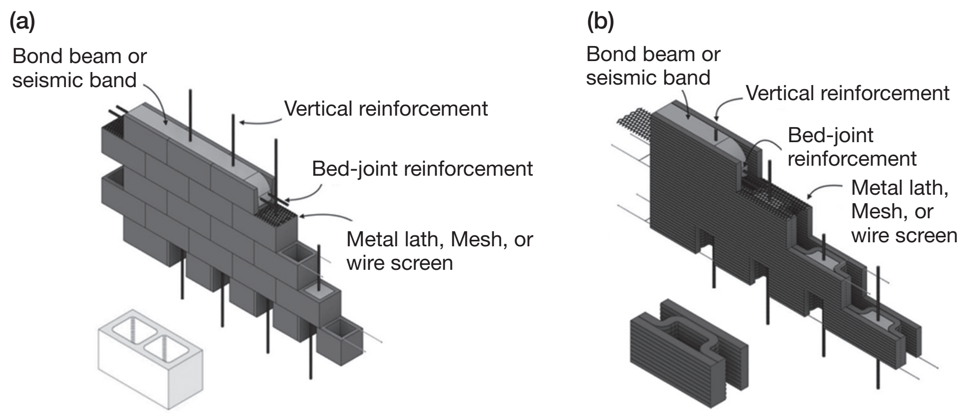
To enable widespread implementation of 3DPC technologies in the construction industry, this project will contribute to filling these gaps by (1) proposing a 3DPC wall design to be used as part of the lateral force resisting system of 3DPC structures; (2) developing strength design equations for the proposed 3DPC wall design, considering a range of potential failure mechanisms, and building upon existing design codes; and (3) determining a suitable response modification factor, also called R-factor, for use of the Equivalent Lateral Force (ELF) procedure (ASCE, 2016)—a widely used seismic design method—in the design of 3DPC housing. The proposed wall design and design equations will be validated using an experimental program on large-scale 3DPC walls subjected to in-plane lateral loading and via computer simulations, and a suitable R-factor will be determined by applying the FEMA P695 methodology (FEMA, 2009). Overall, the widespread implementation of construction 3D printing supported by this project aligns with all five strategic goals of HUD's strategic plan by (1) supporting underserved communities and reducing homelessness; (2) increasing the production of affordable housing; (3) promoting homeownership opportunities; (4) advancing sustainable communities through strengthening climate resilience and energy efficiency; and (5) strengthening HUD's internal capacity through better delivery of HUD's mission and elevating the customer perspective across HUD.

Proposed Wall Design

Three-dimensional printed concrete (3DPC) walls have major similarities with reinforced concrete block (CB) walls in that (1) both include vertical cells, some of which can be grouted; (2) both are built through vertical deposition of "building blocks"—fresh concrete in 3DPC construction vs. hardened concrete blocks in CB construction; and (3) both include weak horizontal interfaces—the layer-to-layer interface in 3DPC construction vs. the block-to-block mortar interface in CB construction. Those similarities have been identified by 3DPC construction companies, such as Apis Cor, which introduced a 3DPC wall design in 2019 that closely follows the cross-section of typical CB walls (see exhibit 1), tested the compressive strength of this design's equivalent 3DPC block, and found it to be comparable to that of CBs (Apis Cor, 2019). Despite those findings, no researchers have performed a comparison between mechanical properties of the various types of 3DPC walls and CB walls. This project takes advantage of the similarity of 3DPC walls to CB masonry walls to develop a wall design that can be used as part of the lateral force resisting system of structures. The objective is to produce information that will be essential to later adoption of such 3DPC design into building codes.

Exhibit 1

Structural Similarity Between 3D Printed Wall and CMU

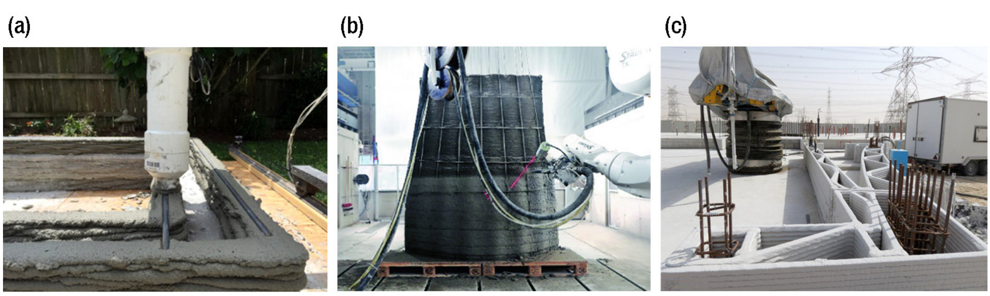


Source: Apis Cor

Primary weaknesses of 3DPC elements built from a layer-by-layer deposition process are the lack of inherent integration of steel reinforcement and the wall-to-foundation and wall-to-floor system connectivity. Three-dimensionally printed concrete buildings in seismic areas need reinforcement to provide lateral deformation capacity and load-carrying capacity. Various strategies have been proposed in the literature for integration of reinforcement in 3DPC elements, such as using steel bars (exhibit 2), integrating preinstalled reinforcement and printed concrete (exhibit 3), using textiles (exhibit 4), and using bar penetration (exhibit 5). However, not all of these solutions have been adopted in field implementation due to either inadequate available studies to demonstrate acceptable performance or insufficiently developed technologies to ensure easy implementation.

Exhibit 2

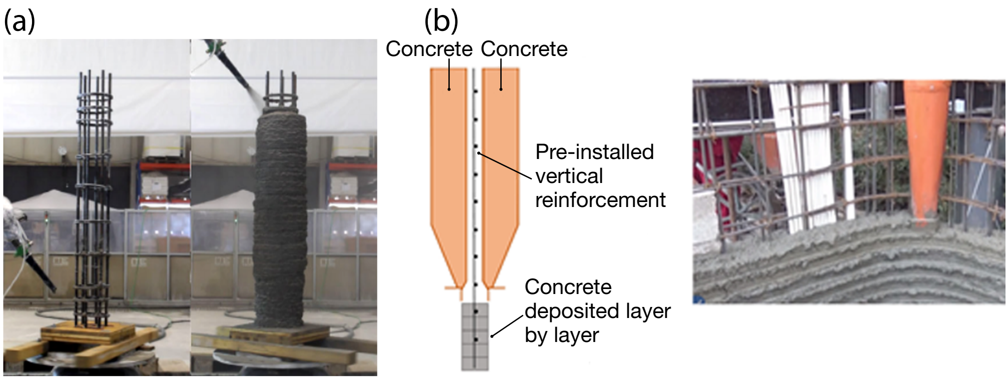
Reinforcement Strategies Using Steel Bars: (a) Placement of Straight Reinforcement Bars in the Print Plane; (b) Placement of Reinforcement in Horizontal and Vertical Directions Externally, Followed by Shotcrete; and (c) Placement of Reinforcement and Application of Grout



Sources: (a) Doris, 2016; (b) Hack and Kloft, 2020; (c) Apis Cor (reported by Block, 2019)

Exhibit 3

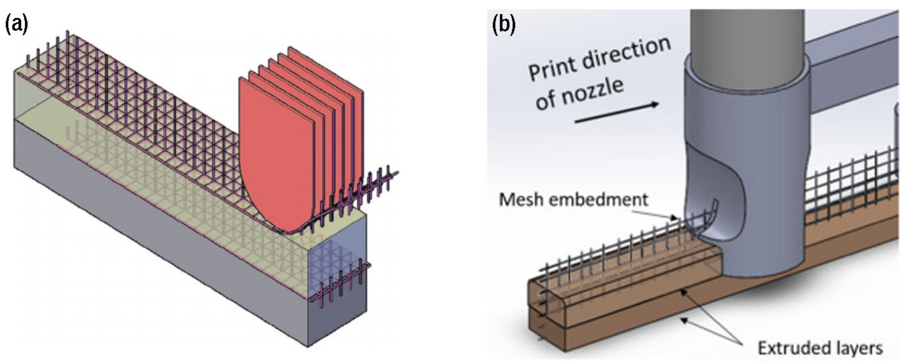
Integration of Preinstalled Reinforcement and Printed Concrete: (a) Shotcrete 3D Printing Around Preplaced Reinforcement Cage and (b) In-Situ Printing Encasing a Preplaced Reinforcement Mat Using a Split Nozzle



Sources: (a) Kloft et al., 2020; (b) Marchment and Sanjayan, 2020b; New China TV, 2016

Exhibit 4

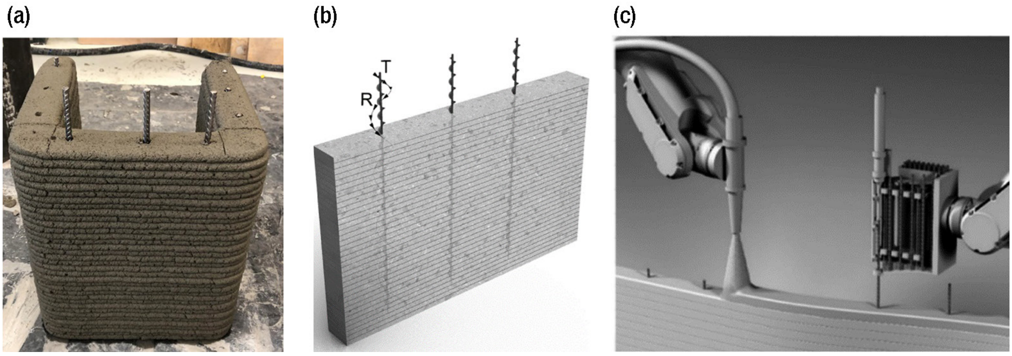
Reinforcement Strategies Using Textiles: (a) Placement of Special 2.5D Textile Between Two Adjacent Printed Layers and (b) In-Process Placement of Galvanized Steel Wire Mesh in the Interlayer Direction



Sources: (a) Mechtcherine and Nerella, 2018; (b) Marchment and Sanjayan, 2020b

Exhibit 5

Reinforcement Strategies Using Penetration: (a) Penetration of 350-mm-Long Steel Bars Through Printed Concrete, (b) Inserting Screws Using a Combination of Translational and Rotational Movement into Freshly Printed Concrete, and (c) Vision for Penetration of Short Reinforcement Bars into Shotcrete 3D Printing Process Using an Automated Process

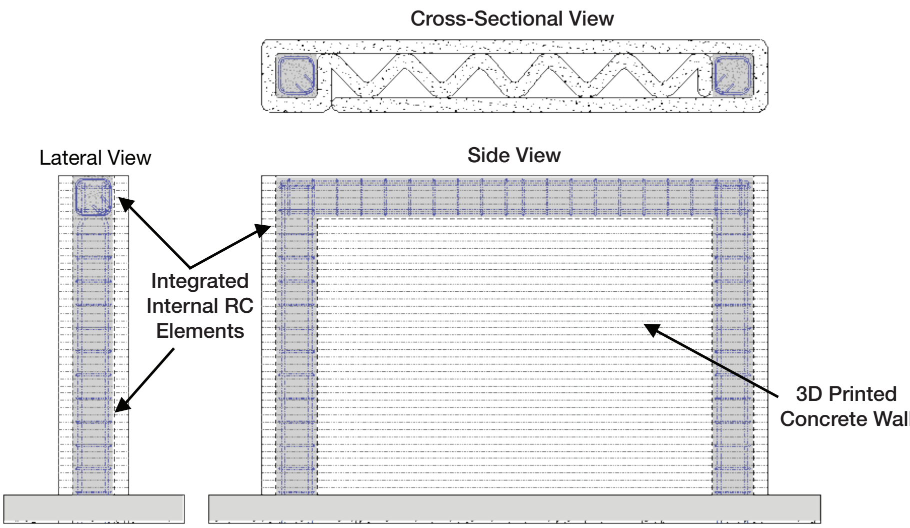


Sources: (a) Marchment and Sanjayan, 2020a; (b) Hass and Bos, 2020; (c) Freund, Dressler, and Lowke, 2020

In this project, the authors have proposed that 3DPC walls (exhibit 6) include integrated internal reinforced concrete (RC) elements that form RC frames, with partial grouting (exhibit 7) over the wall length, as needed. The RC columns may also be thought of as boundary elements, often used in masonry walls as a means of increasing their strength and ductility capacity. This project also uses ladder or truss mesh (exhibit 7) as transverse reinforcement against shear loading and to provide stability during printing. Ladder or truss mesh may also serve as flexural reinforcement for out-of-plane loading. The integrated frame, particularly the presence of the beam, is intended to allow connectivity of floor slabs using connection detailing typically adopted in precast RC framed structures or connectivity of other types of floor or roof systems as dictated by the design. The connectivity of the wall to the foundation can be achieved via the RC column elements through non-contact lap splices (i.e., overlapping longitudinal rebar) or mechanical coupling (exhibit 8). This research will adopt non-contact lap splices between steel bars protruding out of the foundation and the longitudinal and vertical bars of each column, which are practical (or almost a necessity), from a construction point of view.

Exhibit 6

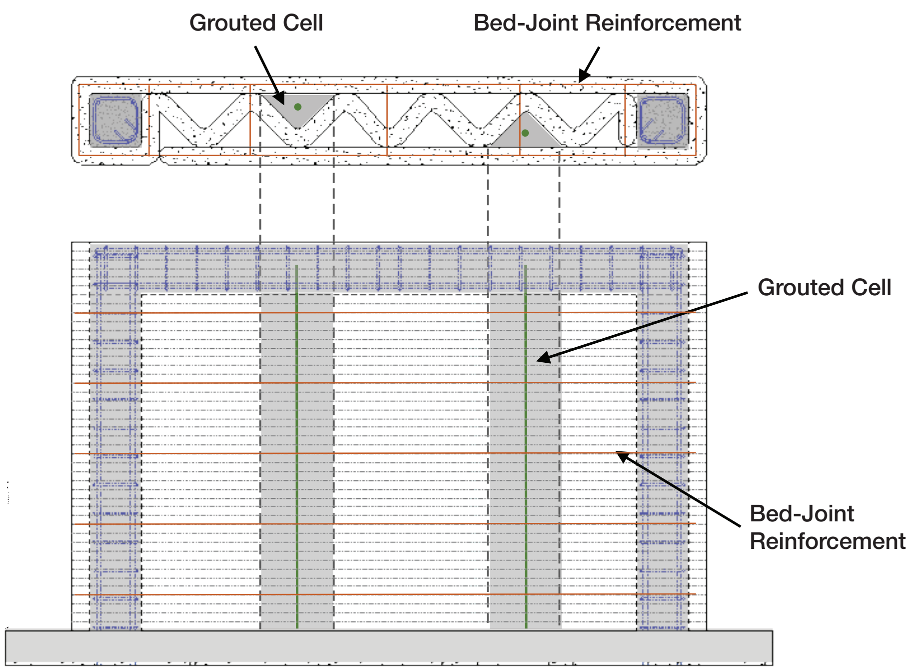
3DPC Wall Design with Integrated RC Frames



Source: Authors

Exhibit 7

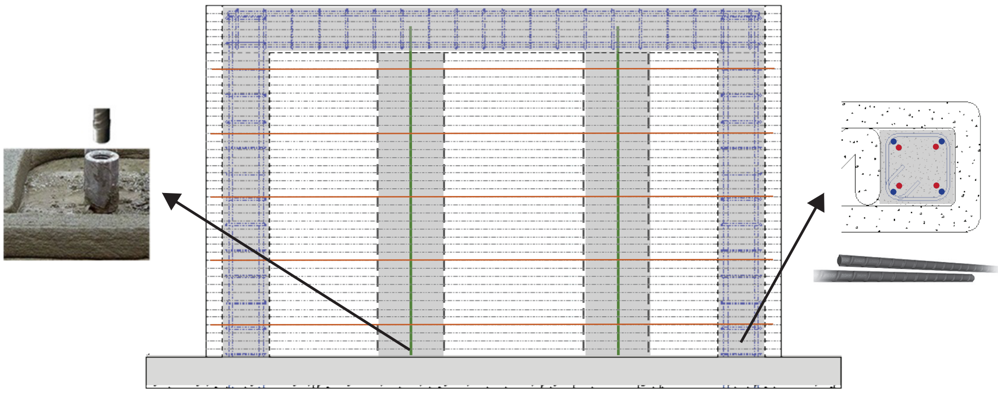
3DPC Wall Design with Integrated RC Frames, Partial Grouting, and (Custom-Made) Ladder Mesh



Source: Authors

Exhibit 8

Connectivity Between 3DPC Wall and Foundation



Note: Apis Cor used 3D printing to go from foundations (shown here—left photo) to a completed house near Moscow in just a day.
Sources: Authors, with photo from Apis Cor (left) and CRSI (right)

Equivalent Lateral Force (ELF) Procedure

To facilitate adoption into building codes, the authors pursue a design procedure for 3DPC housing that is compatible with the ELF procedure of *ASCE 7 Minimum Design Loads And Associated Criteria For Buildings And Other Structures* (ASCE, 2022), which is the procedure widely used by practicing engineers. Implementation of this design procedure requires design equations for the lateral capacity and stiffness of the 3DPC walls, which serve as the lateral force resisting system, and a suitable response modification factor, also called R-factor. The R-factor is used in the ELF procedure to reduce the actual seismic loads, allowing the system, which is otherwise designed through elastic analysis, to yield and deform inelastically. Permission of limited inelastic response results in lower design forces, which leads to structures with smaller size members that are more economical.

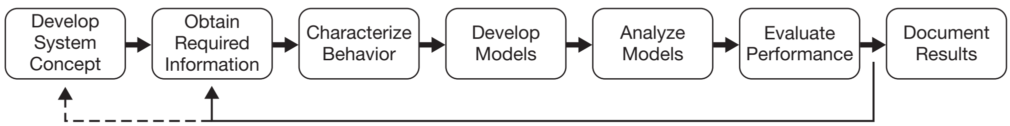
R-Factor

The R-factor for any new structural type, such as 3DPC structures, can be determined by applying the FEMA P695 collapse assessment methodology (FEMA, 2009). Essential components of this methodology are (1) the design of 3DPC building archetypes and (2) incremental dynamic analyses (IDAs) of these buildings with representative ground motions to quantify their collapse margin ratios.

The process of the methodology is summarized in exhibit 9. The first step is to acquire information about the proposed system, such as its potential application, design requirements, and test data. This information will be used in the next step to build archetypes, which are typical representations of the seismic or lateral force resisting system in common applications. The archetypes constitute a general representation of a class of buildings and are used to provide predictions of the performance of this entire new class of 3DPC buildings. To develop archetypes, the authors considered 180 building configurations, resulting from five different plan views. Those plan views, which are shown in exhibit 10, have been obtained (and modified) from available constructed 3DPC buildings combining single- and multifamily dwellings. In this study, using these plan views, the authors designed gravity force resisting systems and seismic force resisting systems for buildings with one, two, and three stories. The building designs covered locations representing seismic design categories B_{max}, C_{max}, and D_{max}, per ASCE 7 (ASCE, 2022) and were designed for four different R factors: 1, 1.5, 3, and 5.

Exhibit 9

FEMA P695 Methodology



Source: FEMA, 2009

The authors developed computer models of the archetypes to investigate their overstrength and collapse margin ratio through static (pushover) and dynamic analyses, respectively. As part of the performance evaluation (exhibit 9), the authors will later use the results from nonlinear static analyses to determine an appropriate value of the system overstrength factor and results from nonlinear dynamic analyses to evaluate the acceptability of a trial value of the response modification factor, R. That process may have to be repeated several times before a suitable R-factor is determined.

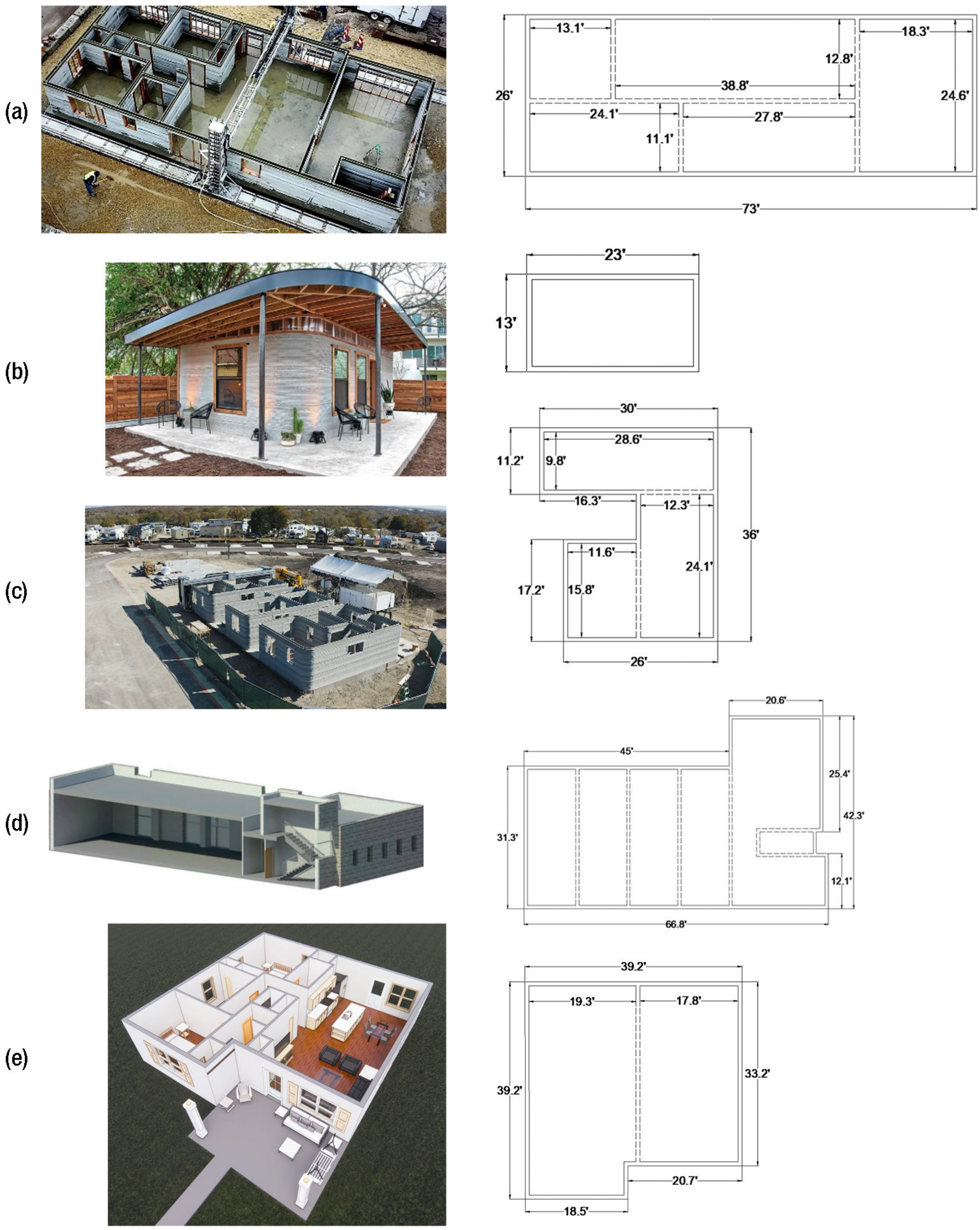
Strength Design Equations

Strength design equations are essential to designing the proposed wall system. To derive design equations, the authors adopted similar design assumptions to those of TMS 402/602-16 *Building Code Requirements and Specification for Masonry Structures* (The Masonry Society, 2016). The adopted assumptions are (1) strain compatibility exists between reinforcement, printed concrete, and poured concrete; (2) all strength derivations should satisfy conditions of equilibrium; (3) the maximum usable strain is 0.0025; (4) plane sections in the undeformed configuration remain planes in the deformed configuration; (5) steel reinforcement has an elasto-plastic stress-strain response; (6) tensile strength of concrete is neglected; and (7) the equivalent average stress of the stress block is $0.8f'_c$ and its depth is $a = 0.80c$ with f'_c, a, and c being the concrete compressive strength, equivalent stress block depth, and location of the neutral axis from the extreme compression fiber, respectively.

The primary (potential) failure mechanisms considered for 3DPC walls subjected to in-plane loading are axial failure, flexural failure, diagonal (tension) shear failure, and interface shear failure, including interlayer shear bonding failure and bed-joint friction failure at the wall-to-foundation interface (exhibit 11).

Exhibit 10

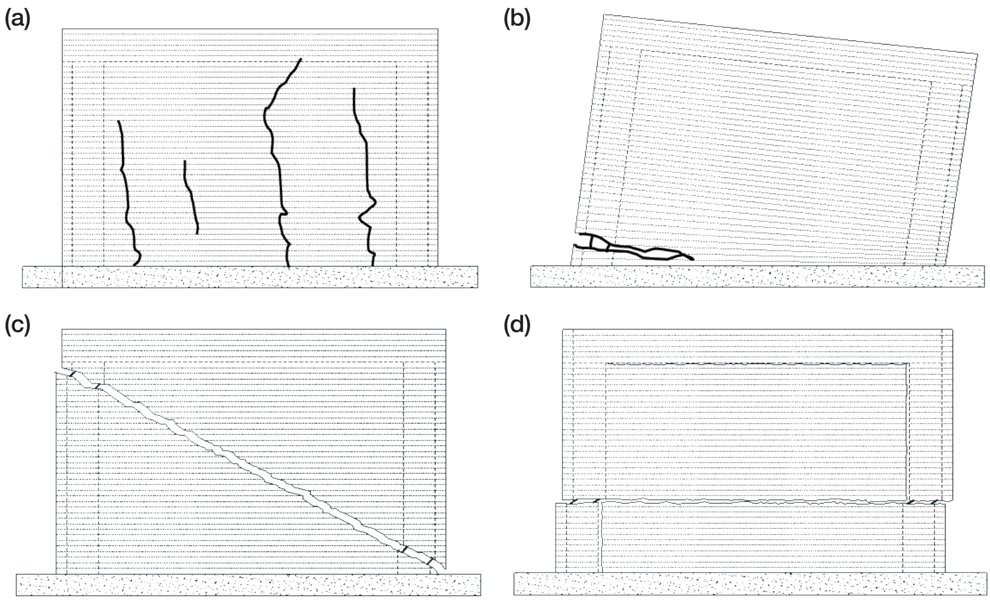
Original Buildings Used in Archetype Development



Sources: (a) Allouzi, Al-Azhari, and Allouzi, 2020; (b) ICON Team, 2018; (c) Jayson, 2020; (d) Kozlowski, 2021; (e) SQ4D, 2020

Exhibit 11

Failure Mechanisms: (a) Axial, (b) Flexural, (c) Diagonal Shear, and (d) Interface Shear Plane



Source: Authors

To develop design equations for the different failure mechanisms in 3DPC walls, the authors built upon existing standards for masonry and structural concrete walls, such as TMS 402/602 (The Masonry Society, 2016), ASCE 7 (ASCE, 2022), ACI 318 (ACI Committee, 2019), and Eurocodes (CEN, 2006). The design equations also adopt basic principles of structural mechanics and are validated via computer simulations. Data from the authors' ongoing experimental program will be used to modify and update these design equations to more accurately predict the response of 3DPC walls (Aghajani Delavar, Chen, and Sideris, 2022a, 2022b). This research will particularly address the lack of experimental data providing information that can significantly support the understanding and future code adoption of 3DPC structures.

Axial Strength

The strength against axial compression failure in 3DPC walls is computed via sectional analysis, considering the contribution of different elements and materials in resisting axial loads. The wall cross-section (exhibit 7) consists of the deposited layered concrete, the integrated internal RC columns, and the grouted cells, all of which contribute to the resistance against axial loads, providing the total axial strength. This strength does not explicitly account for wall buckling and, for that reason, will be applicable only to low-rise construction.

Flexural Strength

In the case of flexural failure, the entire wall—including the deposited layered material, the RC frame, and the grouted cells—is assumed to react as a single element, for example, a deep beam or column, where the "plane sections" assumption is applicable. Horizontal (and vertical) reinforcement provide structural integrity between the 3DPC wall and the integrated internal RC elements. The flexural strength of the 3DPC wall can be computed through sectional analysis.

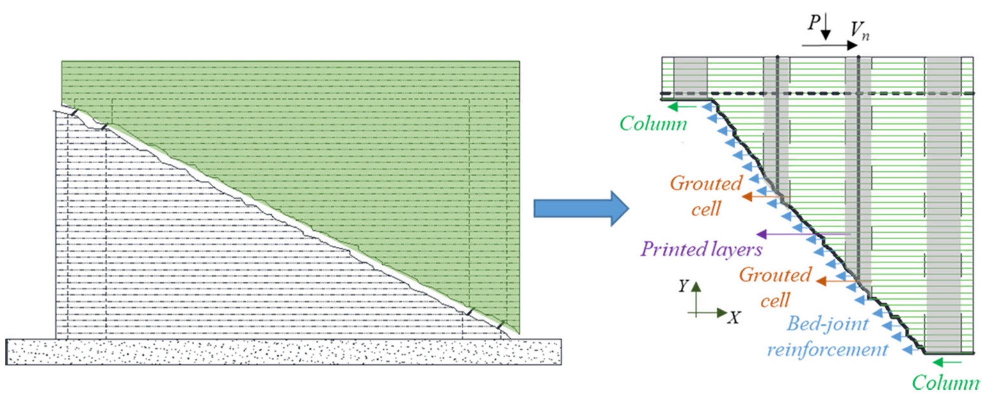
In the proposed 3DPC wall design, wall-to-foundation connectivity is provided through non-contact lap splices, as shown in exhibit 8, at the integrated internal RC columns at their maximum moment location (plastic hinge location). Therefore, to prevent brittle bond-slip failure, lap splices are designed with adequately large splice length and confinement.

Diagonal Shear Strength

Failure is expected to initiate within the 3DPC wall along the compression diagonal strut. The overall shear strength comprises the diagonal tension or shear strength of the infill wall, the shear strength provided by the horizontal bed-joint reinforcement distributed over the infill wall height, and the shear or flexural strength of the RC column. Although the dowel action of the vertical steel bars affects the shear strength, it is not considered herein, in accordance with the approach adopted by TMS 402/602 design code. In 3DPC walls, diagonal shear failure of the infill 3DPC wall may be accompanied by one of two primary responses for the integrated RC frame: (1) shear failure in the columns or (2) flexural failure or hinging of the columns. Exhibit 12 shows the free-body diagram for the x-axis during diagonal shear failure for the proposed 3DPC wall design.

Exhibit 12

Free-Body Diagram of the Wall in Shear Failure in Frame and Shear Failure in Printed Wall



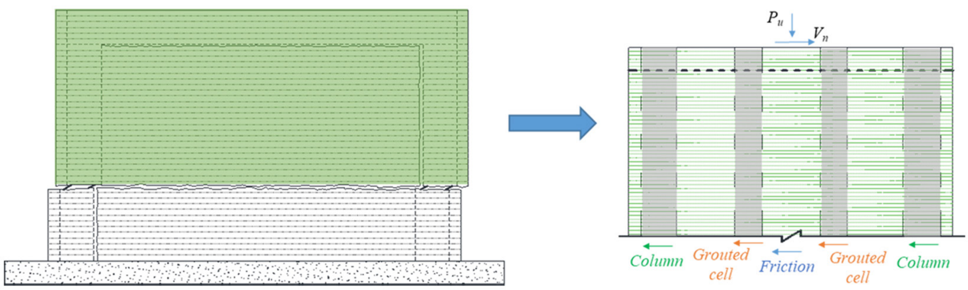
Source: Authors

Interface Shear Plane Strength

The interface shear failure mechanism may occur in the form of interlayer sliding shear failure or as friction failure at the wall-to-foundation interface. The free-body diagram shown in exhibit 13 represents the components of the interface shear strength. By applying equilibrium in the horizontal direction, the interface shear plane strength additively includes the interface bond shear strength (or the shear-friction strength between the layered material and the foundation) and the shear strengths of the columns and grouted cells.

Exhibit 13

Free-Body Diagram of the Wall in Interface Shear Plane Failure



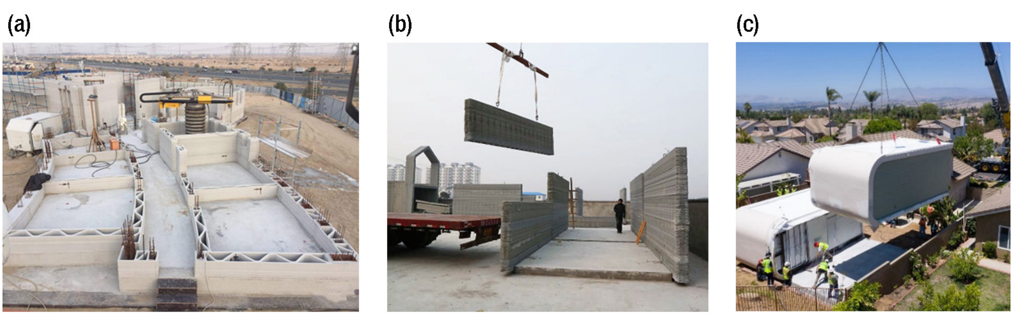
Source: Authors

Construction Process

The construction methods for 3D printed concrete buildings can be categorized in three types (exhibit 14): onsite printing, onsite construction via precast 3D printed elements, and prefabricated 3D printed housing.

Exhibit 14

Construction Methods in 3DPC Buildings: (a) Onsite Printing, (b) Onsite Construction via Precast 3DPC Elements, and (c) Prefabricated 3DPC Housing



Sources: (a) Apis Cor (reported by Block, 2019); (b) Winsun, 2014; (c) Mighty Buildings, 2021

The construction process for the proposed wall design in this project—and, by extension, 3DPC housing—is simple and in accordance with available 3DPC construction methods. In fact, the 3DPC wall construction can be summarized in four steps (exhibit 15):

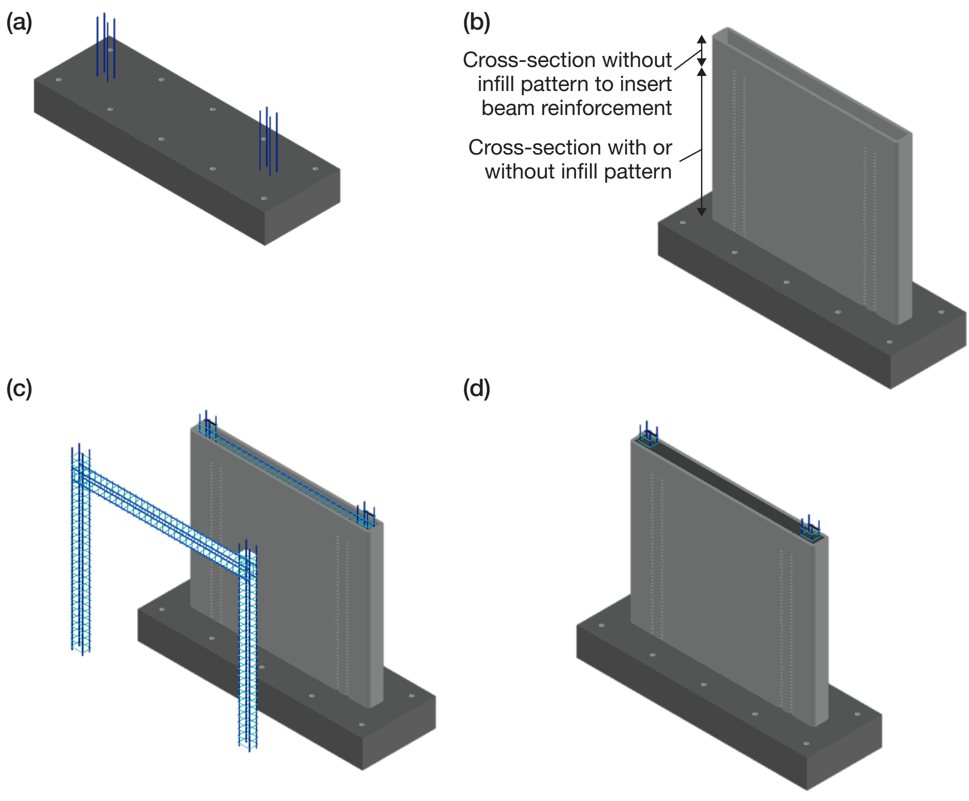
- Step 1: Foundation construction, which should include steel bars protruding for lap splicing with the wall columns.

- Step 2: Onsite printing or onsite assembly of precast 3DPC wall.
- Step 3: Insertion of frame steel cage into the designated location within the wall.
- Step 4: Pouring concrete into the frame columns and beam.

Following Step 4, and after development of sufficient strength, the floor-to-wall connection can be cast. This simple design methodology, together with this practical implementation, can significantly change and broadly affect the homebuilding process by enabling widespread use of construction 3D printing.

Exhibit 15

Construction Process of 3DPC Wall: (a) Step 1, (b) Step 2, (c) Step 3, and (d) Step 4



Source: Authors

Validation

To validate the proposed design equations and the proposed construction process, the authors designed four different 3DPC wall specimens and will experiment through destructive testing of the walls that will simulate seismic loads. Two of those walls are flexure critical and the other two walls are shear critical. In each pair, one wall has infill pattern and the other wall does not. All walls include ladder mesh as the primary shear reinforcement. Also, all walls are subjected to the same axial force per unit wall length. The dimensions and cross-section patterns of the given 3DPC walls are shown in exhibits 16 and 17.

Exhibit 16

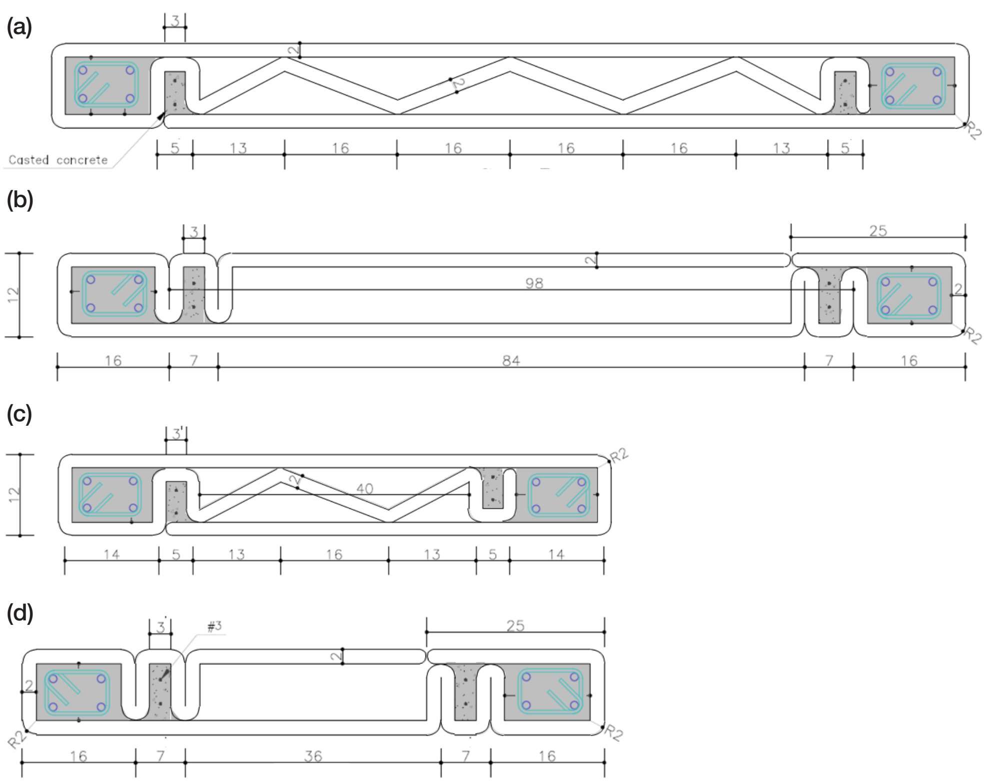
Major Properties of Wall Specimens

Specimen ID	Height (in)	Length (in)	Width (in)	P_u (kips)	Column Reinforcement		f'_{pc} (ksi)	Horizontal Reinforcement		Infill Pattern
					f_y (ksi)	Each col.		f_y (ksi)	Type	
3DPC-1	120	130	12	130	60	4#7 Ties: #3	4.35	70	LM (9 gauge) @4 in	Yes
3DPC-2										No
3DPC-3		82		82		4#5 Ties: #3			LM (9 gauge) @2 in	Yes
3DPC-4										No

LM = ladder mesh.
Source: Authors

Exhibit 17

Cross-Section Patterns of 3DPC Walls: (a) 3DPC-1, (b) 3DPC-2, (c) 3DPC-3, and (d) 3DPC-4

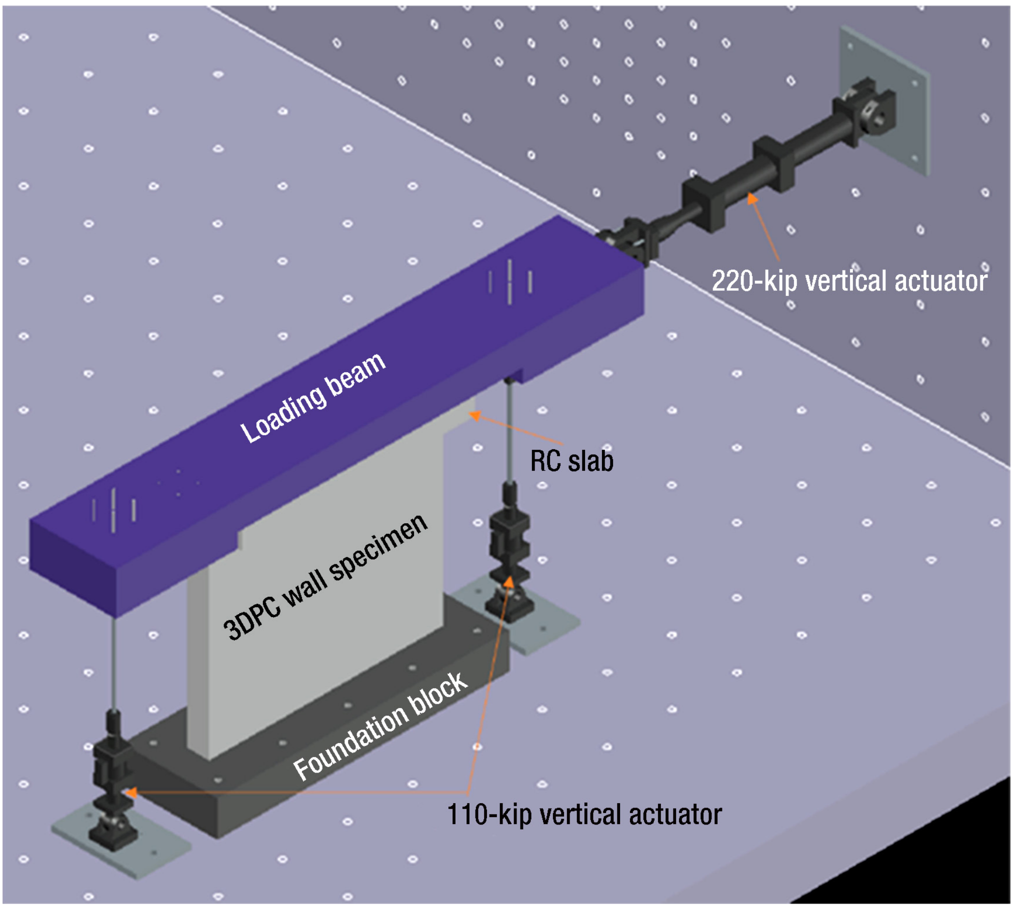


Source: Authors

All four 3DPC walls will consist of a foundation block to allow anchoring to the laboratory floor, internal RC frame, and floor slab. Exhibit 18 shows all components of the testing setup that will be used for all walls, including the wall specimen and the loading setup. The loading setup includes two vertical hydraulic actuators to apply the gravity load and one horizontal hydraulic actuator to apply lateral in-plane cyclic loading, simulating equivalent seismic demands. The response of the proposed wall designs under those loading conditions will be essential to assessing their structural performance during earthquakes.

Exhibit 18

Wall Specimen and Test Setup



Source: Authors

The authors are currently constructing the 3DPC walls. The printed component of all walls has been printed in the Construction Engineering Research Laboratory (CERL) of the U.S. Army Engineer Research and Development Center (ERDC). These printed components will be shipped to Texas A&M University to be used in the construction of the 3DPC wall specimens.

Conclusion

This article proposes a wall design and a building design methodology suitable for seismic applications for low-rise 3D printed concrete buildings. This methodology is currently being validated through computer simulations and via an ongoing experimental study on full-scale 3DPC walls. The proposed design methodology and the associated experimental study will support widespread implementation of concrete 3D printing in the construction industry to achieve all five strategic goals in the HUD *Fiscal Year 2022–2026 Strategic Plan*.

Due to similarities between concrete block masonry and 3DPC buildings, the general design methodology and the construction process for 3DPC buildings follow those for masonry buildings but adopt design equations proposed by the authors. Because this design process for low-rise 3DPC residential and commercial buildings is based on relevant processes used in masonry buildings, it may be more easily accepted by various stakeholders, such as construction technology companies, engineering firms, and local jurisdictions. Despite the increasing need for affordable housing, design and construction processes for 3DPC structures have been limited to date. Such limited availability of design and construction processes may also contribute to integration of the findings and developments of this research effort into design documents that can be used by design engineers. Future research may focus on experimental studies investigating the axial and out-of-plane strength of 3DPC walls.

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