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Designing a Habitat for 3D Concrete Printing in Permafrost Regions

3D concrete printing has the potential to provide a solution to the global shortage of affordable housing. This technology may be particularly suitable for remote regions, where the shortage of labour and materials presents acute challenges. While most projects have focused on the use of the technology to fabricate a structure's walls, this article describes a research effort aimed at printing the entire enclosure using only 3D concrete printing. The design of a habitat for the permafrost regions of Alaska is used as a case study. The design approach was to conceive a parametric housing system based on modular units whose form is inspired by traditional vault design and is amenable to 3D concrete printing.

The proposed design is governed by structural and architectural features, the addressable volume of the robotic arm printer, the desire to avoid formwork, environmental factors such as thermal requirements, foundation type in response to the permafrost, and loads on the structure. While the size of each modular unit is determined by spatial requirements, its exact shape is defined using optimization following structural, thermal, and printing considerations. The printing of a reduced-scale version of the proposed unit validated the design, showing its printability.

Keywords
— additive construction, design for 3D printing, 3D concrete printing, 3D-printed houses, cold-climate design

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Introduction

The world's population is at 7.97 billion people today and growing, with 900 million living in informal settlements with inadequate living conditions.[1] By 2025, these figures are expected to reach 8.2 billion and 1.8 billion, respectively, making the urgency of addressing the current global shortage of homes even more critical. Reducing the severity of this situation requires the development of innovative design and construction technologies. Additive construction technologies, specifically 3D concrete printing (3DCP), can help address the current housing shortage, while also augmenting or transforming the construction industry. In simplified terms, in 3DCP, a 3D model of the part to be printed is used to generate a series of instructions to control an automated fabricator. The 3D model is first sliced into layers, typically horizontal, and then these layers are decomposed into linear or curved patterns, which are linked together to form a continuous toolpath. The toolpath is traversed by a nozzle extruding the material, to create a physical version of the digital model.[2]

Modern additive manufacturing was invented in the 1980s in Japan by Hideo Kodama, who invented two AM photopolymer rapid prototyping systems, in which a mask pattern controls the UV exposure area.[3] Then, in 1983 Charles Hull invented stereolithography, a form of 3D printing technology in which light causes chemical monomers and oligomers to form polymers.[4] Since then, many other forms of 3D printing have been developed. Initially, 3D printing was aimed at developing prototypes of parts and, thus, called rapid prototyping; only later was it oriented towards the development of fully functional parts. The introduction of 3D printing in architecture occurred in the mid-1990s at MIT when a fused deposition model (FDM) machine was acquired and explored both in teaching and research. One of the first applications of this machine was to produce models of Palladian villas and other architectural elements.[5] Then, in 1997 at Rensselaer Polytechnic Institute in New York, Joseph Pegna introduced 3DCP technology.[6] In the following year, at the University of Southern California, Khoshnevis et al. developed contour crafting, in which the key idea was to print the contour of walls, then place reinforcement bars or cages, and finally pour additional concrete to surround the reinforcing elements in place.[7] In 2009, Lim et al. at Loughborough University in the United Kingdom created a simpler process for 3DCP.[8] Since then, research in 3DCP has grown exponentially at different universities, government agencies, and within companies around the world.[9]

The promise of 3DCP stems from a number of potential advantages. By enabling the automated fabrication of parts directly, each from potentially different 3D models, 3DCP enables mass customization, which can lead to higher-value outcomes and thus user satisfaction. For the construction industry, automation translates into lower labour requirements, which can lead to increased safety, lower construction times, and lower construction costs. With 3DCP it is possible to extrude composite functionally graded

1 Worldometer, "World Population," accessed September 18, 2022. https://www.worldometers.info/world-population/
2 Ian Gibson, David Robson, Brent Stucker and Mahyar Khorasani, *Additive Manufacturing Technologies*, third edition (Cham, Switzerland: Springer Nature, 2021). https://doi.org/10.1007/978-3-030-56127-7
3 Petar Kocovic, "Chapter 1 – History of Additive Manufacturing," in *3D Printing and its Impact on the Production of Fully Functional Components: Emerging Research and Opportunities*, ed. Petar Kocovic (Hershey: IGI Global, 2017), 1–24.
4 Idem.
5 Larry Sass, *Reconstructing Palladio's villas: An analysis of Palladio's villa design and construction process,* PhD thesis (Cambridge: Massachusetts Institute of Technology, 2000), 385.
6 Joseph Pegna. "Exploratory investigation of solid freeform construction," *Automation in Construction*, vol. 5, no. 5 (February 1997): 427–437. https://doi.org/10.1016/S0926-5805(96)00166-5
7 Behrokh Khoshnevis, Satish Bukkapatnam, Hongkyu Kwon, Jason Saito, "Experimental investigation of contour crafting using ceramics materials," *Rapid Prototyping Journal*, vol. 7, no. 1 (March 2001): 32–42. https://doi.org/10.1108/13552540110365144
8 Seung Hyun Lim, Thanh T. Le, John Webster, Richard Buswell, Simon Austin, Alistair Gibb, Tony Thorpe, "Fabricating construction components using layered manufacturing technology," in *Proceedings of the Global Innovation in Construction Conference*, Loughborough, UK, 13–16 September 2009, 512–520.
9 Fuyan Lyu, Dongliang Zhao , Xiaohui Hou, Li Sun and Qiang Zhang, "Overview of the Development of 3D-Printing Concrete: A Review," *Applied Sciences*, vol. 11, no. 21 (October 2021): 9822. https://doi.org/10.3390/app11219822

materials (FGMs), for which the gradient of component materials can vary in response to functional requirements. With concrete this can be realized, for example, by partially replacing river sand with cork granules as the aggregate in response to insulation requirements, thereby avoiding the construction of complex wall assemblies involving multiple layers and many trades.[10] Thus, the use of FGMs can simplify construction processes, requires fewer joints (reducing building pathologies and lowering maintenance costs), increases safety, and lowers construction times and costs. FGMs can also enable optimized environmental performance and material savings, resulting in energy savings and, therefore, lower operating costs and a reduction in the ecological footprint. 3DCP also avoids the use of formwork, which allows the creation of complex forms and intricate surface textures at no additional cost, which increases design freedom. Finally, 3DCP facilitates the use of construction materials derived from in situ resources, which results in reduction of transportation requirements, thereby decreasing cost, CO_2 emissions, and ecological footprint. In summary, 3DCP enables the construction of affordable, customized, high performance, and aesthetically pleasing buildings, while increasing safety, reducing construction time, and lowering environmental impacts.

The application of 3DCP in the construction of structures for commercial purposes has followed three fundamental strategies. The first strategy involves parts of the building being 3D printed in the factory or on site and then put in place. This avoids having to deal with constraints imposed by the printing system, such as limitations of the printing envelope or the need for formwork when printing overhangs. An example of this approach is the house printed by the Chinese company Winsun in 2014.[11] The second strategy is similar to the first, except that the walls are printed in place and the roof is either built with another material (e.g., wood) or pre-printed and hoisted into place. Some recent examples include a two-story house by Kamp C in Westerlo, Belgium in 2020; a house built for Habitat for Humanity by Alquist in Virginia, USA, in 2021; a detached 94 m^2 single-storey home with two bedrooms built by TU Eindhoven in the Netherlands in 2021; and House Zero by ICON in Arizona, USA, to name a few examples of 3DCP homes.[12] In this context, most 3DCP approaches to date have mainly focused on the construction of walls. The third strategy, however, is to fully print the entire structure in place. The demonstration of a 3D-printed house by the Italian company Wasp using clay in 2021 included two interconnected dome-shaped structures, which were topped by prefabricated skylights to completely enclose them.[13] Two years earlier, a Penn State team participating in the NASA 3D Printed Mars Habitat Challenge successfully printed a concrete structure comprising two interconnected cylinders transitioning to cones at the top, resulting in the first fully enclosed structure printed at architectural scale.[14] This paper describes research building on that effort with design of 3DCP homes in remote permafrost regions of Alaska, describing various aspects of design.

10 Flávio Craveiro, Helena Bártolo, A. Gale, José Duarte and Paulo Bártolo, “A Design Tool for Resource-Efficient Fabrication of 3D-Graded Structural Building Components Using Additive Manufacturing,” *Automation in Construction*, vol. 82 (October 2017): 75–83. https://doi.org/10.1016/j.autcon.2017.05.006

11 Lucy Wang, “Chinese Company Assembles 3D-Printed Concrete Houses in a Day for Less Than $5,000 each.” April 6, 2014 https://inhabitat.com/chinese-company-assembles-ten-3d-printed-concrete-houses-in-one-day-for-less-than-5000-each/ Last accessed November 7, 2022.

12 e-architect, “3D-Printed Model Home by Kamp C in Westerlo.” https://www.e-architect.com/belgium/3d-printed-model-home-kamp-c-westerlo. Last modified July 7, 2020. Architizer, “House Zero.” https://architizer.com/projects/house-zero/ Last accessed September 18, 2022. Matt Hickman, “Habitat for Humanity and Alquist Partner for the East Coast’s First 3D-Printed Habitat Home,” *The Architects Newspaper*. Last modified July 7, 2020. https://www.archpaper.com/2021/07/habitat-for-humanity-alquist-partner-east-coasts-first-3d-printed-habitat-home/ Eindhoven University of Technology, “Printing our way out of the housing crisis: ‘It is desperately needed,’” April 30, 2021. https://www.tue.nl/en/news/news-overview/30-04-2021-printing-our-way-out-of-the-housing-crisis-it-is-desperately-needed. Last accessed November 7, 2022.

13 Wikipedia, “Tecla House,” *Wikipedia*. https://en.wikipedia.org/wiki/Tecla_house. Last modified August 8, 2022.

14 Penn State, “Designing Sustainable Homes on Mars and Earth.” https://www.psu.edu/impact/story/designing-sustainable-homes-mars-earth/. Last modified April 8, 2019.

15 Gonçalo Duarte, Nathan Brown, Ali Memari, and José Duarte, "Learning from Historical Structures under Compression for Concrete 3D Printing Construction," *Journal of Building Engineering,* vol. 43 (November 2021): 103009. https://doi.org/10.1016/j.jobe.2021.103009

16 Nicholas A. Meisel, Nathan Watson, Sven G. Bilén, José Duarte and Shadi Nazarian, "Design and System Considerations for Construction-Scale Concrete Additive Manufacturing via Robotic Arm Deposition," *3D Printing and Additive Manufacturing*, vol. 9, no. 1 (February 2022): 35–45. http://doi.org/10.1089/3dp.2020.0335

Precedents

The goal of the proposed design and construction approach was to develop an expedited method for providing affordable housing to indigenous peoples in Nome, a community in a remote area of Alaska. The design approach was based on two sets of precedents. The first is a set of vernacular examples from Alaska, including igloos built in ice and mountain shelters built using dry stack stone. The common theme in both cases is the use of block-layering techniques, which constitute a "primitive" form of additive construction. However, whereas for igloos the blocks are laid in radial layers with a capstone, in mountain shelters the blocks are laid out in horizontal layers. Such techniques can be found in many other cultures around the world. The second set of precedents consists of historic examples from erudite architecture, namely vault-and-dome construction techniques. These include structures based on Roman and gothic arches that were also built following brick- or stone-layering techniques. Particularly, the Gothic arch constituted a suitable precedent, as the degree of inclination of the dome's walls is higher, which constitutes an important restriction when printing concrete without formwork. Several types and domes were studied, and the cross-vault was selected, as described further below. A more detailed discussion of using vernacular and erudite vault-and-dome construction techniques as a precedent for printing enclosing structures can be found in Duarte et al.[15]

System Constraints, Design Requirements, and Design Approach

The design approach was to conceive of a parametric housing system based on modular units with shape and configuration suitable for 3D printing of the entire structure—including grounding, walls, and enclosure. The proposed shape is impacted by the features of the printing system, the desire to avoid formwork, applicable loads on the structure (self-weight, snow, wind, earthquake), and thermal requirements for the structure and the foundation type, as well as spatial requirements of the home. Constraints associated with the printing system included the reach of the robotic arm in x, y, and z directions above and below ground, the maximum printing angle, and the associated minimum wall thickness. For a description of the printing system, see Meisel et al.[16] Formwork was avoided to simplify construction, decrease material waste, and lower construction cost. Structural requirements included the need to avoid collapse of freshly deposited concrete during printing without the use of any temporary support, and the ability to resist vertical and lateral loads after the concrete hardens. Thermal requirements included isolating the structure to create a comfortable living environment in the interior and to avoid heat transfer between the structure and the supporting ground to avoid melting the permafrost soil, which could endanger the structure.

The resulting design is a modular unit with approximate dimensions of 12 × 12 × 16 ft (approx. 3.7 × 3.6 × 4.9 m) and inspired by historic cross-vault structures with pointed arches to avoid exceeding the maximum printing angle. The dimensions are a compromise between printing constraints, height of the interior space, and spatial programme and requirements. The idea is that one unit could meet minimal programmatic requirements (kitchen, bedroom, etc.) or be combined with other units to accommodate larger spaces (living room, etc.). Parametric variation of one unit is also possible within the constraints imposed by the printing system. Several variations of the structural unit are being considered for further development. For the initial foundation, one solution foresees creating an open crawl space to allow air circulation between the top of ground and the underside of the structure, with concrete columns printed on top of wooden or steel piles that extend through the active layer and into the permafrost zone or down to bedrock. The other solution consists of a thermal raft slab-on-grade foundation such that crushed rocks and insulation assist in avoiding the transfer of heat to the permafrost. Above this foundation, one option consists of a double shell structure with an insulation layer of foam in between, and the other a single shell with the insulation layer on the inner side of the structure. While the size of each modular unit is determined by spatial requirements, the exact shape is defined following optimization based on both the structural and thermal performance considerations.

Review of the Conventional Home Construction in Rural Alaska

Home building in Alaska should consider various challenges, including harsh environmental conditions due to snow and frozen ground, as well as wind and earthquake loads. Moreover, energy efficiency and health considerations are also of primary interest. Many guides and manuals have been developed by the Cold Climate Housing Research Center (CCHRC)[17] with the objective of guiding all stakeholders in the design and construction practices that consider various critical aspects for construction in Alaska. Furthermore, given that 40% of the Alaska's 300 rural communities are in areas without much access to infrastructure — including roads, clean water, and sewers — healthy home construction is of critical importance for people living in those regions.[18]

The project reported in this paper explored for the first time the feasibility of using 3D printing in rural Alaska. A review of the vernacular architecture in Alaska made clear that it was built such that not much fuel would be needed to keep the inhabitants warm.[19] However, the influence of modern American home construction techniques that were not developed for extreme cold conditions have negatively impacted quality of life. The walls, floors, and roofs have details that result in thermal bridges, which lead to loss of significant interior heat through conduction.

17 CCHRC, "Remote — A Manual," Cold Climate Research Center, 2013. http://cchrc.org/library/remote-manual

18 USDA, "Alaska Rural Homeownership Resource Guide," U. S. Department of Agriculture, 2017.

19 HUD, "Alaska Native Housing Needs," Outreach Session Proceedings Report, Office of Native American Programs, U.S. Department of Housing and Urban Development, 2011.

In addition, these houses have been costlier to build and maintain because they are hermetically sealed and prevent the flow of fresh air, thus requiring air conditioning systems. Lack of access to fresh air and breathing in circulated interior air accumulates interior air pollutants over time — such as mould caused by moisture and humidity built up, bacteria, and cleaning chemicals — which collectively cause and exasperate chronic respiratory illnesses, creating an unhealthy living environment.[20] In addition, much of the required wood for construction purposes has to be imported, which means more expensive construction.

Review of Foundation Systems Used in Alaska Home Building

Residential buildings in Alaska use both shallow and deep (i.e., pile) foundations. In suitable soil conditions, shallow foundations may be placed directly in contact with the frozen ground, but more often the requirement to maintain thermal equilibrium in the frozen ground dictates that shallow foundations be placed on a gravel berm or a layer of suitable sandy soil, preferably with, but sometimes without, insulation.[21] Pile foundations do not require open excavation, which can significantly disturb the permafrost. Structures supported by piles are elevated above the ground surface to prevent heat loss through the floor from warming the frozen ground, and to allow cold air to refreeze the active layer in the winter. Proper consideration of the interaction between the building and the frozen ground in the permafrost zone is necessary to guarantee a successful design of the home. Permafrost is frozen ground with temperature below 32°F (0°C) for over two consecutive years. However, if the permafrost layer starts to experience heave due to the repeated thaw-freeze cycle, the foundation and the structure can have settlement causing damage to the structure. Therefore, the design needs to prevent the heat transfer between the structure and the soil to maintain the bearing capacity of the supporting soil.[22]

Structural System Definition

The focus of the structural system study was on a solution that permitted the 3D printing of a full continuous concrete shelter to avoid structural joints as much as possible. Given the current state of the art in concrete printing, the objective was to find solutions that avoided complex reinforcement solutions. The study thus developed design solutions with compressive stresses as the main load-resisting mechanism in the walls that could be printed without formwork; the use of carbon or steel fibres mixed with the concrete was selected as an appropriate reinforcement for the compression-dominated design to control shrinkage and thermal cracks in the structure.

After a study of conventional structures, a set of solutions was selected for further study during the first stage of our explorations (Figure 1).[23] All these solutions had a footprint of 12 × 12 ft

20 CCHRC, "Remote—A Manual," Cold Climate Research Center, 2013. http://cchrc.org/library/remote-manual.

21 Orlando Andersland and Branko Ladanyi, *An Introduction to Frozen Ground Engineering* (New York: Springer, 1994). https://doi.org/10.1007/978-1-4757-2290-1

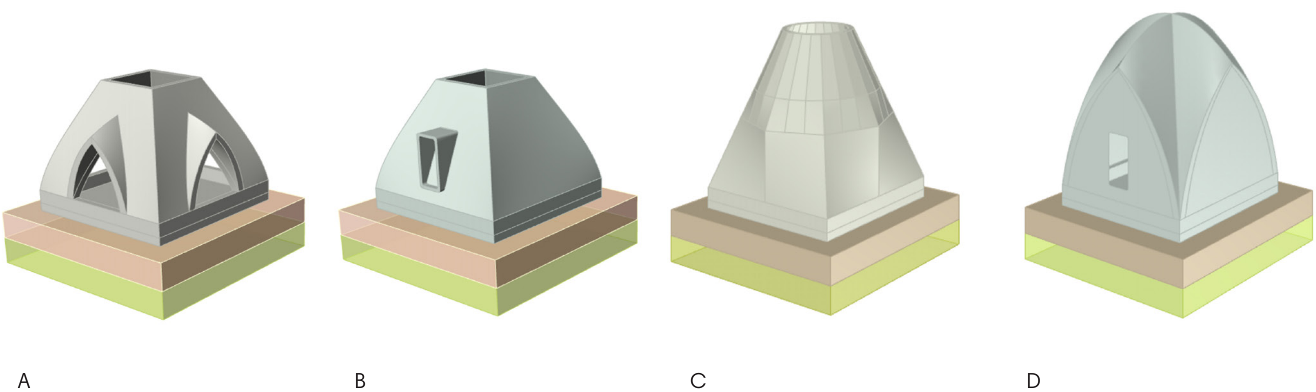
22 Terry McFadden, *Design Manual for New Foundations on Permafrost* (North Pole, AK: Permafrost Technology Foundation, September 2000).

23 Duarte et al, "Learning from Historical Structures."

(approx. 3.6 × 3.6 m) and a height between 8 and 13 ft (approx. 2.4 m and 3.9 m), since printing fully enclosed spaces requires either a dome or arch to remain in compression, or a prefabricated flat element on top. While the solutions shown in Figure 1 are all assumed to be slab-on-grade, the same structures were also considered as elevated options. As noted in the introduction, the proposed designs benefit from the full potential of 3D printing and maximizing automated construction. The main advantages of printing the full structure, including grounding, walls, and roof, are (1) simpler and cheaper construction, and (2) having fewer joints, thereby decreasing the likelihood of air and moisture leaks, which is particularly important in harsh environments like Alaska. Each printed structure may constitute a single-space shelter, a tiny house for a small household, or a room of a house for a larger household that could be composed of several units clustered together and a small loft space depending on the internal height of the enclosure.

Solutions A and B in Figure 1 have the same basic shape for the roof structure, a so-called cloister dome. Both solutions have a truncated top due to printing restrictions, which could contain a skylight. They differ in the way openings are introduced, with Solution B requiring the use of prefab elements for making horizontal flat surfaces. Solution C is based on a traditional dome shape from ancient Persia called a squinch, which transitions from a square footprint to a domical space, with some advantages in terms of 3D printing. Solution D is based on a cross-vault with pointed arches and is the tallest of the four structures, but it is also the one that is fully enclosed at the top. This range of solutions demonstrates the design flexibility of 3D printing. Based on preliminary evaluation of the four options in terms of feasibility, Solution D was selected for further development.

Fig. 1 Selection of structures with vaulted roof structures for further study: slab on grade version with foundation consisting of floating slab supported directly over the active layer. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.



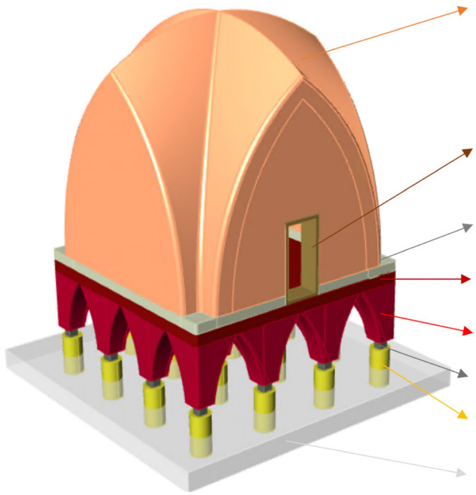


Fig. 2 The different parts potentially composing the 3D printed monolithic vaulted structure: foundation, grounding, slab, walls, and roof. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

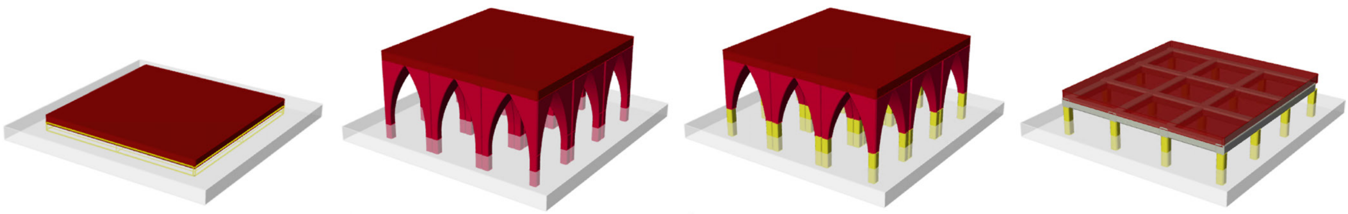
24 Naveen K. Muthumanickam, José P. Duarte, Shadi Nazarian, Ali Memari, Sven G. Bilén, "Combining AI and BIM in the design and construction of a Mars habitat," in *Routledge Companion for AI in Architecture*, eds. Imdat As and Prithwish Basu (Abingdon, UK: Routledge, 2021), 251-279.

Parametric Design

These structures can be potentially composed of foundation, grounding, slab, walls, and roof (Figure 2). The parametric definition of the structure allowed for a quick exploration of possible design alterations such as changing the height, curvature, footprint, openings, and foundation shape in response to structural, aesthetic, or functional requirements.
This parametric model was implemented in Grasshopper and Rhino and constituted the generative module of a larger design platform powered by artificial intelligence (AI), which will also include a structural and thermal simulation module and an optimization module.[24] This platform permits one to analyse the trade-offs between different solutions and to find those with better performance from the selected structural and thermal viewpoints. This extended design platform and its use in the design of a scale version of the cross-vault unit is briefly described further below.

Foundation

Four solutions were studied for the foundation (Figure 3). The first solution consists of a floating slab supported directly on the ground (Figure 3A). This configuration presents difficulties posed by the heat of the concrete material during printing and curing, which may cause heat transfer to the permafrost soil. In addition, this configuration makes it difficult to thermally isolate the interior, which is warmer when occupied, from the permafrost soil layer. It is possible to overcome these difficulties with the design of the foundation, consisting of a bed of crushed stone deposited on grade and placing a rigid insulation layer prior to printing. The thermal resistance and thickness of the rigid insulation will be determined to avoid heat transfer

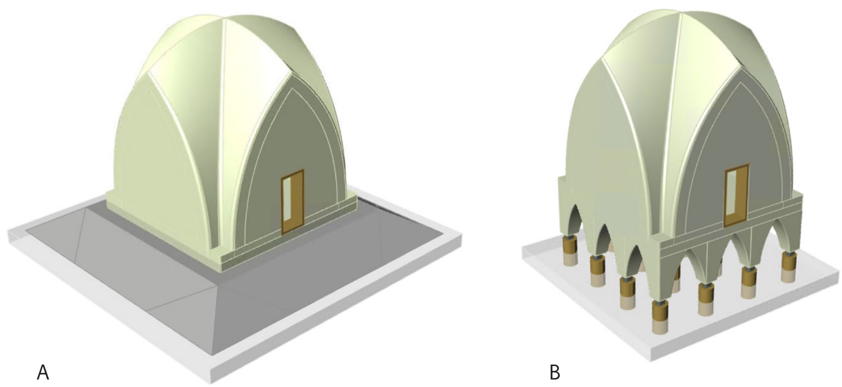


A B C D

to the ground (Figure 3B, C, and D). However, raising the main structure would be more effective. This approach creates an isolating air cavity (as in an open crawl space) between the warmer, inhabitable structure and the frozen permafrost soil underneath. Following this approach, the second solution for the foundation is to print pillars to form the entire foundation both above and below grade (Figure 3B). This solution requires the printing system to reach several metres deep into the active layer and within the permafrost region and presents the disadvantage of the deposited material, which is hot while curing and, as mentioned above, may cause heat transfer and potential melting of the soil in the permafrost region. Thus, this solution is not a desirable option due to thermal and structural challenges. In the third solution (Figure 3C), the piles are made of another material — wood or steel — placed into the ground and topped by small platforms on which the 3D-printed vaulted concrete grounding would be printed. In the fourth solution, (Figure 3D), a concrete slab platform would be printed on top of a wooden or metal bed supported on piles, creating a "podium" on which the structure can be printed, which requires additional materials that could reliably support the 3D-printed structure. Thus, Solutions A and C were considered for further design development (Figure 4).

Fig. 3 Solutions for the foundation: (A) floating 3D printed slab on ground, (B) slab on 3D printed concrete grounding on piles in the same material, (C) slab on 3D printed concrete grounding on piles in other material (wood or steel), and (D) concrete slab 3D printed on cable grid structure.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

Fig. 4 The structure considering two different foundation solutions: (A) slab on grade and (B) raised slab.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.



A B

Grounding

The grounding is the part of the structure that creates an isolating air cavity between the inhabitable structure and the ground surface underlain by active and permafrost layers, something like a crawl space. It consists of a set of cross-vaulted shapes supported on the wooden or steel piles in Solution C of Figure 3. The goal of the design is to enable as much airflow as possible through the cross vaults while still transferring the structural loads of the floor slab above down into the individual piles below. These geometric trade-offs were analysed, and the constraints for the height needed to create sufficient ventilation were considered, while limiting the height to reduce lateral seismic induced forces in the columns. Two different approaches were considered to create this crawl space. In the first approach, the grounding is printed, and in the second, it consists of a graded slab mounted on the piles, on the top of which the concrete slab would be printed. This hybrid solution can simplify printing but would lead to a more complex shelter by involving other construction systems. Therefore, the first approach was selected for the design. Considering the height needed for the curved arch shape of the supporting columns, the result was to minimize the height of the pile above ground surface to about 0,6 m, with the rest of the height for ventilation provided by the printed columns for a total open space height of about 1,5 m above the ground surface. The shape of the grounding could be made of “homogeneous” printed concrete material or “heterogeneous” material with an exterior shell made of stronger, heavy concrete and the interior core made of lightweight concrete, in which sand aggregates of the shell are partially replaced by light expanded clay or cork granules, which has the advantage of producing a lighter structure with increased insulation properties. The latter solution has two options: in the first option, the inner lighter concrete is poured or printed after the outer shell is printed, whereas in the second option, the outer shell and the inner lighter core are printed simultaneously using a FGM printing strategy, where the aggregate content of the mixture is changed during printing. The second solution requires a more sophisticated (and, hence, more expensive) printing system. In addition, the added insulation provided by mixing cork or other insulation granular materials would be minor compared to the level of R-values needed for Alaska. Therefore, foam insulation was considered in the design as explained below.

Slab

The slab is the part of the structure that rests on the grounding and mediates between the grounding and the interior. It provides a flat, horizontal basis for the floor of the shelter. It may be made of ordinary homogeneous concrete or, alternatively, functionally graded concrete as described above, which also brings additional benefits, including lighter weight (which benefits the foundation design and lowers seismic loads) and a lower carbon footprint. While such a solution is ideal for most climates, it is quite challenging to design parameters that will provide the desirable thermal resistance for the concrete. Therefore, even though an FGM could be used in an Alaskan construction project, significant supplemental insulation would still be needed.

Walls

Walls are the vertical elements that enclose the interior space. Because of the vaulted shape of the roof, the printed walls can be short, providing just a basis for the roof. Two possibilities were considered for the structure of the walls: solid (single shell) or hollow (double shell) (Figures 5 and 6, respectively). The former may use homogeneous concrete or functionally graded concrete with insulative "layers" with an increased grade of lightweight material towards the top (with the potential benefits mentioned earlier), and the insulative aggregates printed on the exterior side of the wall. The latter has the advantage of being lighter, using less material,

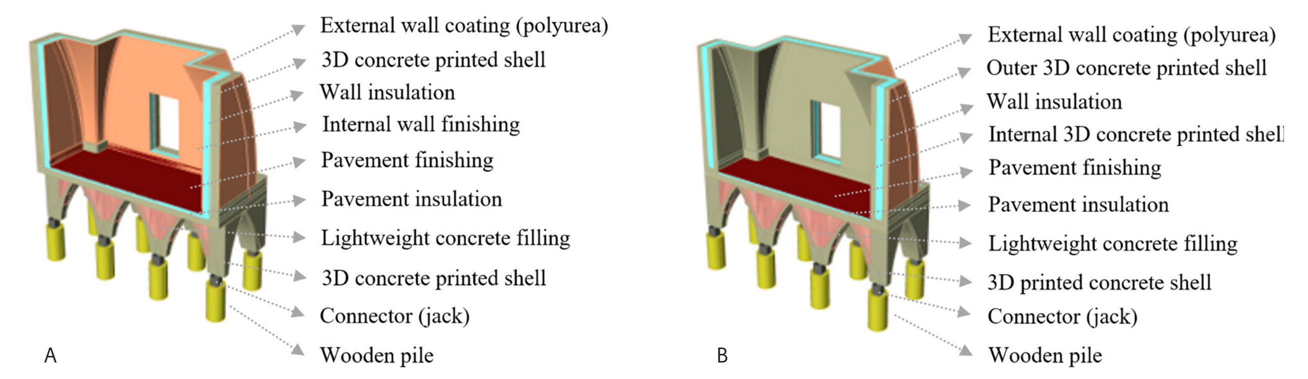


Fig. 5 Wall solutions considered for the raised slab structure: (A) single shell and (B) double shell. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

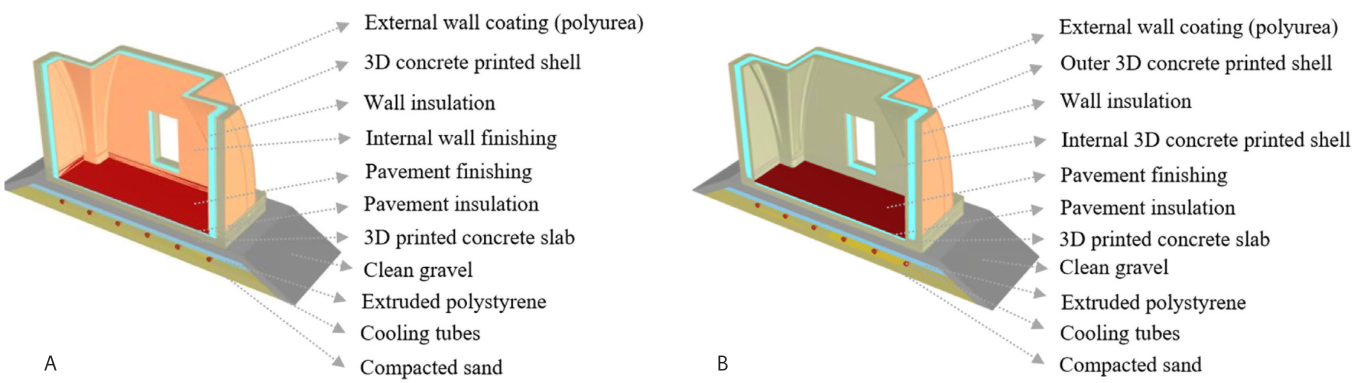


Fig. 6 Wall solutions considered for the slab on grade structure: (A) with single shell and (B) double shell.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

and having improved insulation properties, but it makes printing of the vaulted roof on the top more challenging. The hollow cavities maybe filled in with insulation foam or granules, but this hybrid solution complicates construction. Further study will permit identification of the most appropriate solution considering structural, thermal, printing, and construction elements.

Roof

The roof is the part of the structure that encloses the interior space. As mentioned above, using a vaulted or domed structure for the roof permits 3D printing of the entire structure, avoiding formwork, simplifying construction, and providing a unibody, sealed-and-enclosed environment by decreasing the number of joints. The exact shape of the dome will be determined after structural analysis and considering printing constraints, including the reach of the robotic arm and toolpath design. Like the remaining parts of the structure, the roof may be printed using ordinary concrete or lightweight concrete, which could be homogeneous or potentially functionally graded, with the grade of lightweight aggregates increasing toward the top for improved structural performance.

Envelope and Insulation

In addition to the structural requirements, the extreme environmental conditions in Alaska necessitate careful consideration of the building envelope and its performance. As noted above, a major requirement is thermal separation of the conditioned indoor space from the foundation to avoid melting the permafrost. In addition, the surface temperature of the floor is of particular concern in Arctic climates, since it impacts the liveability of the house and requires the floor surface temperature to be as close to the ambient temperature as possible. The walls and roof also have stringent insulation requirements. For the Alaskan climate, the required R-values range from around R-20 for above-grade walls to around R-50 for roofs, depending on the geographic location. In traditional rectilinear construction, such values could be achieved through a variety of methods. The proposed geometries for 3D printing the proposed structures require different strategies due to their curvature and gradual transitions between the wall and the roof. Given these challenges, several insulation approaches were considered. In addition to the conventional single material use in all layers, FGM offers a solution to integrate insulation materials (e.g., cork granules or Styrofoam balls) into the concrete to improve various properties and attributes, including being lightweight, which favourably affects structural and seismic design and improves thermal resistance and ecological footprint. However, since concrete itself generates less than R-1 per inch (approx. 2.5 cm) depending on density, other insulating materials are required. One possibility is to spray foam on the interior shell or on the exterior shell, which can adhere to custom shapes and offer R-values

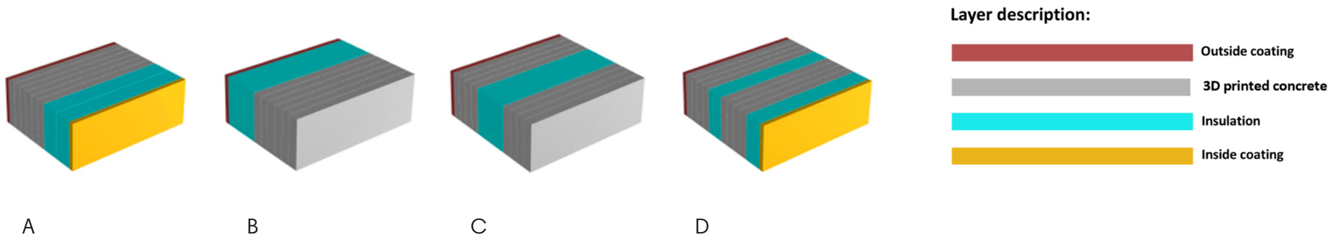


Fig. 7 Potential thermal insulation strategies: considering the printing of a single (A and B) or a double shell (C and D) and the placement of the insulation layer (A) inside, (B) outside, (C) in between the shells, or (D) a combination of both. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

of up to R-7 per inch (approx. 2.5 cm) for closed-cell foams (Figure 7A and B). Another option is to print double walls and roofs, which creates some structural advantages, and then fill the voids with insulative materials, either in the form of foam or rigid panels, depending on the geometry (Figure 7C). In this method, special care would be given to potential thermal bridging, which is subject to how the two layers are connected for structural load transfer. Another possibility is to employ a combination of strategies, that is, have a double wall shell with two layers of insulation, one in between the wall cavity and another on the interior shell (Figure 7D). For a complete discussion of insulation strategies, see Brown et al.[25]

25 Nathan Brown, José Duarte, Ali Memari, Ming Xiao, Shadi Nazarian, Gonçalo Duarte, and Zhengyu Wu, “A Comparison of Thermal Insulation Strategies for 3D Printed Concrete Structures in Cold Regions,” *Proceedings of the 6th RBDCC – Residential Building Design and Construction Conference*, State College, PA, March 4–6, 2022.

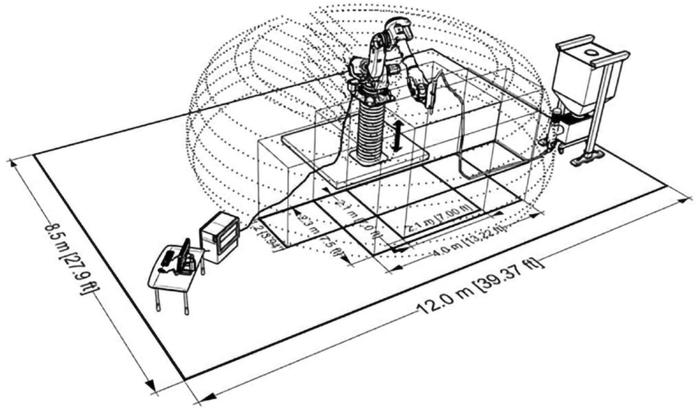
3D–Printing System and Process

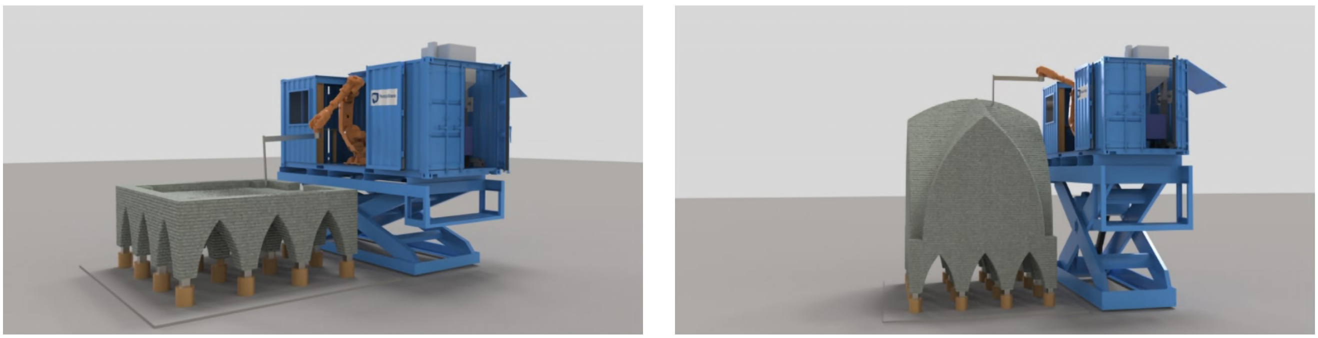
Two printing systems are necessary to implement the proposed design. The first is used to develop and test the concept at the laboratory scale. The second will be utilized to print the prototype of a house in Alaska. These two systems are briefly described below.

The laboratory printing system consists of a mixer-pump for mixing and extruding the dry mixture, a silo that contains the dry mix and feeds the pump, and an industrial six-axis robotic arm with a 2.8 m reach (Figure 8). The dimensions of the printing volume can vary depending on the length and orientation of extensions added to the robotic arm, which can be adjusted to be suitable for the size of the structural unit. To print larger structures, the system can be extended to include a large silo capable of storing enough of the dry mixture to print one structural unit, a water tank in case there is no water source near the construction site, and a second robot to install door and window frames in place. In yet another configuration, the system may include a second mixer-pump and a second silo, to enable the printing of FGMs. In short, in this version of the system, each silo holds a mixture with a different gradient and is connected to a pump, the mixtures from each pump are mixed with a dynamic nozzle,

Fig. 8 Diagram of the basic configuration of the printing system in the laboratory, which includes a mixer-pump, a small silo, and a robotic arm. The printing area can be increased to meet the size of the proposed structural unit by adding an extension to the robotic arm.
Developed at Additive Construction Laboratory – AddCon Lab, PSU, in 2020, by Nate Watson.

Fig. 9 Printing process of the proposed shelter at two different stages of completion. The depicted "printer-in-a-box" system is currently being developed to facilitate deployment and mobility.
Developed at Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Nate Watson.





26 Flávio Craveiro, Helena Bártolo, Paulo Bártolo, Shadi Nazarian, and José Duarte. "An Automated System for 3D Printing Functionally Graded Concrete-Based Materials," *Additive Manufacturing*, vol. 33 (May 2020): 101146. https://doi.org/10.1016/j.addma.2020.101146

and by varying the relative speed of each pump, it is possible to change the gradient of the printing mixture.[26]

The system being developed to print in Alaska is a revised version of the laboratory system, enhanced to overcome two of its limitations and enable the printing of full-scale structures on site. The first concerns the mobility of the system, for which two configurations are being studied. In the first, the system is redesigned into a "printer-in-a-box" system, so that it can be moved using standard shipping methods. As this configuration imposes some restriction regarding how the system can be moved on site, the second configuration foresees the robot being mounted on a rover. Figure 9 shows the printing of the proposed design with the first configuration.

27 Gonçalo Duarte, José Duarte, Ali Memari, Nathan Brown, Juan Pablo Gevaudan, "Towards a model for buildability in concrete printing based on material properties," *Construction and Building Materials*. (Submitted on October 3, 2022).

Materials

Different kinds of mixtures for 3D printing, including cementitious, non-cementitious (i.e., geopolymer), and clay-based mixtures have been developed for various printing applications. More extensive work and testing has been carried out with cementitious mixtures, particularly a mixture developed in collaboration with Gulf Concrete Technologies (GCT). This mixture is a blend of ordinary Portland cement, lime, pulverized limestone, especially graded masonry sand, fibres, and admixtures with a maximum particle size of 1 mm (table 1).

MATERIAL COMPOSITION	PERCENTAGE
Pulverized limestone	<2–6%
Lime	<30%
Crystalline silica	<50–70%
Portland cement	<50%
Calcium sulfoaluminate cement	<5–12%
Cellulose	0.2–2%
Starch	0.2–2%

Tab. 1 GCT material composition.

Material properties of this mixture of concrete, including compressive strength, setting time, and flowability, are presented in table 2. The compressive strength of the material was tested in accordance with ASTM C-109. The Vicat needle test (ASTM C-191) was performed to measure the initial and final setting times and a flow table test (ASTM C-1437) was conducted to evaluate the flowability of the mixture. An ASTM C39 test obtained within 48 hours of printing the concrete structural elements and performed on a printed cylindrical specimen showed 749 psi compressive strength, and an ASTM C78 test performed on a printed rectangular beam showed 485 psi (modulus of rupture). Detailed information on the experimental programme conducted to characterize the material is provided in Duarte et al.[27] The main objective of this programme was to characterize the rheological and strength properties of the material over time.

COMPRESSIVE STRENGTH	TEST AGE (DAYS)	STRENGTH (MPA) [PSI]
	3	15.12 [2192]
	7	17.95 [2602]
	28	24.55 [3560]
SETTING TIME	INITIAL SET (MIN)	FINAL SET (MIN)
	80.7	143
FLOWABILITY	FLOW (CM)	
	23.3	

Tab. 2 GCT material properties.

This information was then used to develop a structural analysis software to predict the behaviour of fresh state concrete in structures during the printing process to inform the design with 3D printing in mind, as explained further below. The goal, however, is to develop and test printable mixtures out of local materials with appropriate rheological and strength properties.

Toolpath Design

Concrete printing involves a complex system of interdependent variables involving the printing system, materials, and design. Successful printing of stable and accurate structures depends on tuning the system to the correct combination of values for these variables. Structural stability is related to printing quality, which depends on variables related to the pump and robotic arm, which, in turn, are related to the properties of the concrete mixture. These variables determine the dry mix feed and water flow rates, which determine the water-to-dry-mix ratio and, together with the pump rotation speed and the nozzle size, determine the required robotic arm travel speed. Research has been performed to obtain this information and model the relationships among the different system variables.[28] This research informed the software development for automatically generating toolpaths that guarantee high print quality by accounting for material deformation (Figure 10), considering key printing settings, such as the extrusion flow rate, layer printing time, and the size of the part in terms of the number of filaments and layers.[29]

The toolpath design software is implemented in Rhino and Grasshopper. The Grasshopper plugin HAL also is used to convert the toolpaths to the high-level programming language used to control the industrial robots. The robots have two operating modes: manual mode, in which the manipulator movement is under manual control and the speed is reduced to a maximum of 250 mm/s; and automatic mode, in which the

28 Negar Ashrafi, Shadi Nazarian, Nicholas Meisel and José Duarte, "A Grammar-Based Algorithm for Toolpath Generation: Compensating for material deformation in the additive manufacturing of concrete," *Additive Manufacturing*, vol. 55 (July 2022): 1–20. https://doi.org/10.1016/j.addma.2022.102803.

29 Gonçalo Duarte, José Duarte, Nathan Brown, Ali Memari, Juan Pablo Gevaudan, "Design for Early-Age Structural Performance of 3D Printed Concrete Structures: a Parametric Numerical Modeling Approach," *Automation in Construction*. (Submitted on June 28, 2022).

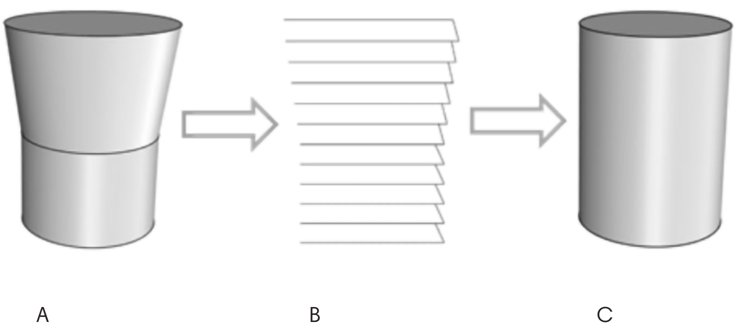


Fig. 10 Diagram representing the strategy for designing a cylinder with compensation for layer width deformation: (A) compensated designed cylinder, (B) compensated toolpath, and (C) resulting printed cylinder. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2020, by Negar Ashrafi.

safety function of the enabling three-position switch (one of the two safety functions of robots) is bypassed so that the manipulator can move without human intervention and the robot moves at full speed autonomously.

Construction Sequence

The construction of one unit with a double shell is depicted in Figure 11 for a raised-slab unit. The process starts with (A) the placement of piles into the permafrost soil followed by the jack connectors, then (B) proceeds with the printing of the grounding shell, which (C) is then filled with lightweight concrete. This makes the structure lighter, and if the lightweight concrete has insulating beads, it can provide some thermal insulation properties. Regardless, thermal insulation of the structure is provided in the interior. Next, (D) the floor slab is printed on top, then (E) the base wall, followed (F) by the placement of the opening frame. Then, (G) the printing of the roof structure is initiated, to (H) obtain the complete structure. In the solution

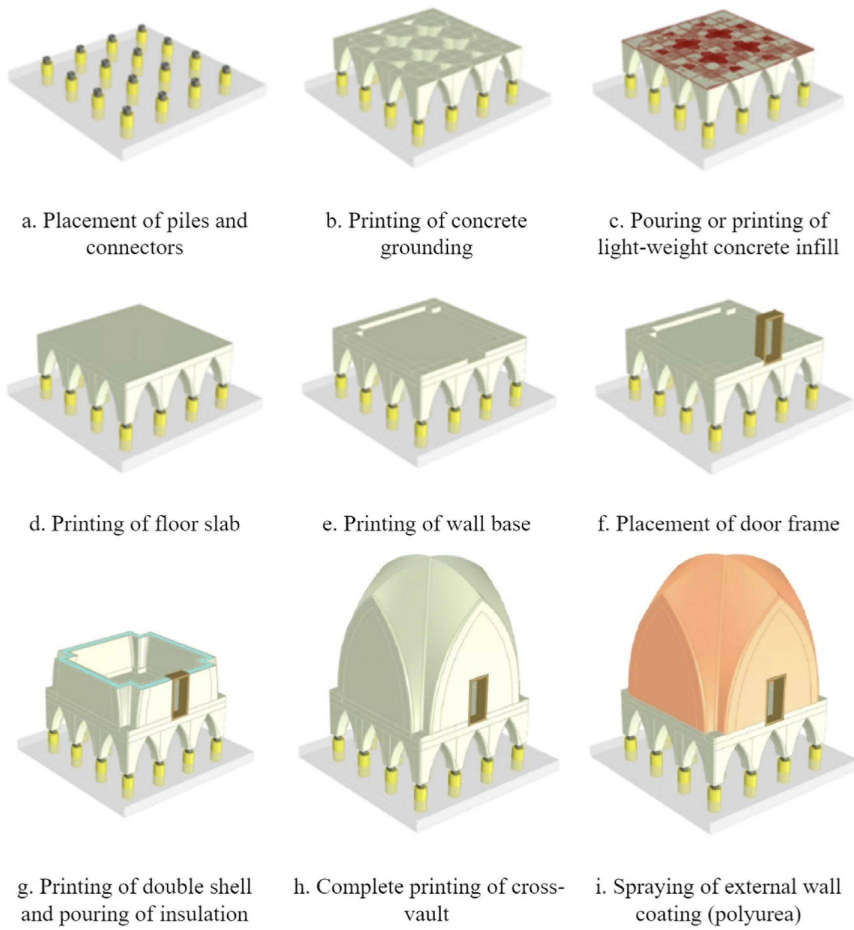


Fig. 11 Construction sequence of an elevated, cross-vault unit with double shell. The printing of shell and deposition of insulation in between may occur at the same time. The construction sequence of a unit with single shell is very similar, expect that insulation is placed after the shell is printed. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

with double shell, the insulation foam in between the two shells may be printed at the same time or sprayed after a certain number of layers are printed. Once the printing is over, (I) polyurea is sprayed on the exterior surface to provide waterproofing and protect the unit from abrasion or impact. In the solution with a single shell, construction proceeds much in the same way, except that insulation is sprayed after the shell is printed. As noted earlier, it is also possible to use rigid insulation on flat parts of the interior surfaces. Furthermore, insulation can also be milled to fit the curved shape of the shell and then mounted; this solution is more expensive and more delicate to build but provides a cleaner finishing.

Combining Units to Create Larger Houses

Larger houses can be obtained by incrementally adding new units (Figure 12). The printing of additional units can take place sequentially, one after the other, or over time, as the functional needs and financial ability of the

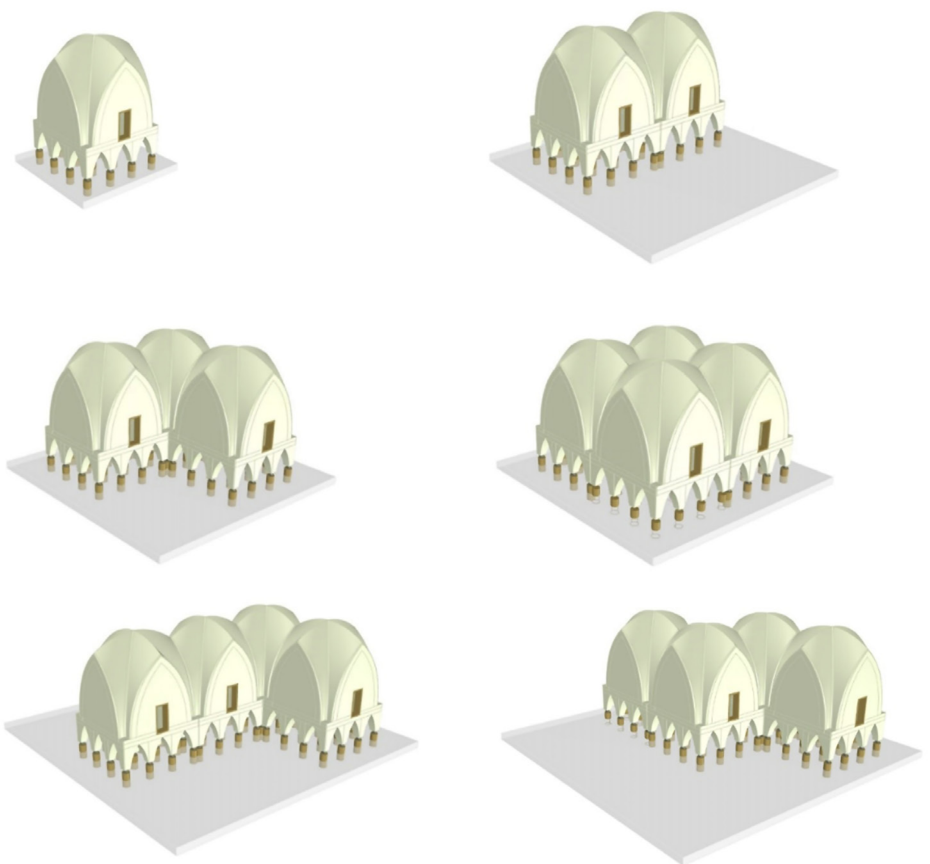


Fig. 12 Incremental addition of units to form larger houses, which may occur over time and take different configurations. Each unit may have different and one or more uses: kitchen, living-room, dining-room, bedroom, bathroom, and so on. The exact configuration and uses will depend on the household profile, including the number of members and social-economic level. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

30 Gonçalo Duarte, José Duarte, Nathan Brown, Ali Memari, Juan Pablo Gevaudan and Shadi Nazarian, "Structural Optimization of Overall Shapes in 3D Concrete Printing," (in preparation).

household increase. Houses may acquire different configurations as different number of units may be added on different sides. The possibility of combining units with different roof shapes is also noteworthy.

Optimizing a Scaled Unit Design

As noted in the section on parametric design, a platform was developed to optimize the design of vault structures. This platform supports a design optimization workflow for 3D concrete printed (3DCP) structures that comprises the following steps: (i) a generator of overall shapes, from a parametric model that was established based on shape grammar rules; (ii) a gradient-free constrained optimization process that uses 3D-printed concrete constraints to select the best designs and performs a partial structural analysis considering a preliminary toolpath to select the best solution; (iii) feeding of a refined toolpath for the best solutions; (iv) a simulator of the early-age structural behaviour that performs finite element analysis at each layer and checks whether the structure collapses during printing. The workflow was used in the design of an open cross-vault to print at one-third scale.

The constrained optimization was performed in Grasshopper using the component *Radical* from the plug-in *Design Space Exploration*. The optimization of the cross-vault structure consists of a typical constrained structural optimization problem, in which the objective is to minimize structural mass while subjected to a set of constraints. Four types of constraints were considered, namely structural constraints, toolpath constraints, geometric constraints, and system constraints. A more in-depth description of the optimization process is discussed in an upcoming publication.[30] Structural constraints comprised two types of sub-constraints: (i) serviceability sub-constraints that were expressed as a function of the lateral and vertical displacements when subjected, respectively, to a wind and deadload and serviceability load combination; and (ii) a proxy for printability that involved the finite element analysis of the largest identified cantilever at 35%, 70%, and 100% of its fabrication. The numerical modelling considered material properties, which would change every time a new layer is added, and the early age modes of collapse, namely, of plastic collapse, elastic buckling, and flexural collapse. Toolpath constraints considered two forms of constraints. First, a minimum acceptable printing time per layer in the counterweight region of 34 seconds is considered to filter solutions whose legs presented an excessively small cross-section area. Additionally, the algorithm of toolpath compensation for material deformation was implemented and automatically adjusted the toolpath design for layers with a printing time shorter than 34 seconds. Second, it included extrusion-based constraints, such as the material extrusion rate, as well as to the robot motion speed, which directly influence the extruded filament design. Geometry constraints included the maximum overhang criterion of 60 degrees,

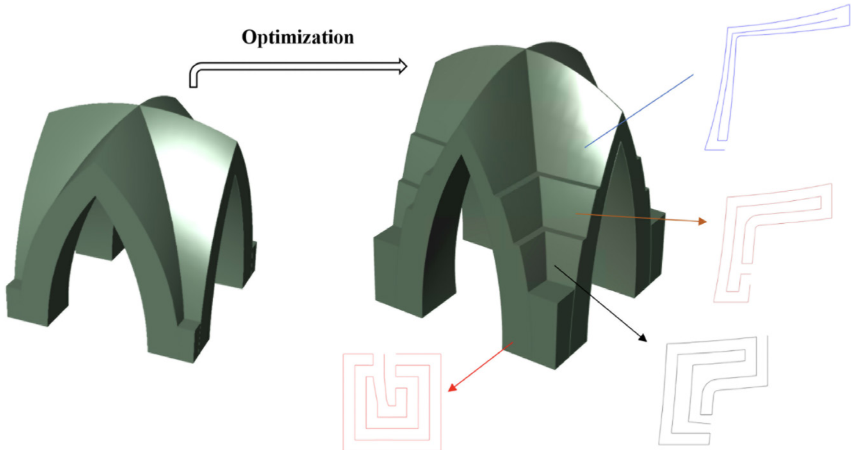


Fig. 13 Optimized design of a cross-vault unit to print at 1/3 scale and respective toolpath design at each stage of the leg fabrication. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2022, by Gonçalo Duarte.

and system constraints limited the dimensions of the cross-vault to the printing envelope of the robotic arm, which resulted in a limitation of the length of the vault to be 1.20 m. The final design of the cross-vault with a height of 1.30 m and a length of 1.12 m, as well as the corresponding toolpath, which considers compensation for material deformation is presented in Figure 13.

Test Print of One Scaled Unit in Laboratory

To validate the design optimization process described above, the cross-vault was fabricated by printing one leg a time, until closing and respective top part. The goal of printing a complete leg at a time resulted from the decision of avoiding excessive travel moves, which would lead to additional printing time and material volume. The cross-vault was successfully printed (Figure 14), which validated the design approach and highlighted the potential of the 3DCP technology to fabricate enclosures.

Discussion and Conclusion

This paper describes the design of a habitat to be 3D printed in Alaska, where cold temperatures and permafrost soil pose significant challenges. In particular, it explains the design requirements that stem from the cold weather conditions and the constraints imposed by features of the printing system.

The shell design proposed for the envelope of the habitat includes foundation, walls, and roof. By continuously printing these construction elements, it is possible to decrease the number of joints and lower the

Fig. 14 Printed 1/3-scale prototype of the optimized cross-vault design.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2022, photo by José Duarte.

possibility of water and air leaks, thereby making it easier to maintain adequate living conditions indoors and avert building pathologies.
Of course, for the actual construction project, the potential for differential foundation settlement, thermal gradients, and structural overloads that can cause cracking would need to be considered in designing and developing the details. The proposed cross-vault design was selected after reviewing different vault designs inspired by historic structures, considering their printing feasibility, whether they fitted in the printing system's envelope, the ease of generating the toolpath, and the possibility of printing the roof. Two solutions for the foundation were selected after considering traditional solutions for cold climates, namely slab on grade and raised slab on piles. The latter seems to be better as it creates a "crawl space" in between the structure and the permafrost soil, preventing the heat from the interior heated space from melting the permafrost soil. Despite presenting increased printing difficulties, the preferred solution for creating the crawl space is to print several interconnected small vault-domes, filled with insulative lightweight concrete topped with a layer of insulation before printing the slab. Several solutions for insulating the walls and the roof were considered. As the extreme cold weather requires substantial thickness, it is not possible to meet insulation requirements by printing FGM alone, despite the architectural design benefits. The more promising solution is to print a double-wall shell with foam insulation in between, which would avoid difficulties in placing rigid insulation panels on to a double-curved form, while keeping the aesthetic qualities of the printed surface.

Two printing systems are being used to print the shell-shapes habitat designs. Both include a robotic arm, which presents increased design, six axes of freedom, and deployment flexibility when compared to gantry-based systems. The first printing system is fixed in place, and it is used to print prototypes, whereas the second system is a further evolved mobile version of the first that can be shipped in a container and/or mounted on a rover to print habitats on rugged sites. A platform incorporating generative, simulation, and optimization components was developed to support the design of the shell structure of the habitat. The generative component encodes the rules for designing vault and dome structures, as well as the toolpaths to print them, while considering the features of the printing system. The simulation part performs structural analysis of the selected design schemes, and it can be extended to include other forms of analysis, such as environmental comfort. The optimization component permits identification of various design solutions with better performance. This platform was used to design a one-third-scale prototype of the cross-vault that was successfully printed in the laboratory, thereby validating the approach.

It is noteworthy that the proposed design approach is supported by a multidisciplinary team of researchers with diverse scientific and cultural backgrounds, which adds to and enriches the depth of knowledge, as a necessary condition to successfully develop the technology. Research encompasses three main areas, including design of materials, design of the printing system, and exploring the necessary design processes with the goal to model the complex relationships among the various variables associated with these areas. The variables can be divided into six categories: environmental variables, material composition, material properties, printing settings, toolpath design, and building design. The ultimate goal is to develop a mathematical model of the printing process and to control it in order to achieve high printing quality and structural stability. This is mainly an applied research project based on the development of cases studies such as the one described in this paper, which is centred on the design aspects related to the 3D printing of housing in rural and permafrost regions of Alaska.

The described effort is only the starting point for developing the full design of a housing system. Future work will include detailing the interior design of the habitat, including technical installations; extending the design platform to incorporate thermal comfort; development of the mobile printing system; and running printing tests at full scale.

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Conflict of Interest:
Drs. Duarte, Bilén, and Prof. Nazarian own equity in X-Hab 3D, Inc., which has an interest in this project. Their ownership in this company has been reviewed by the University's Individual Conflict of Interest Committee and is currently being managed by the University.