NOME COMMON COUNCIL
WORK SESSION AGENDA

MONDAY, JUNE 06, 2022 at 5:30 PM
COUNCIL CHAMBERS IN CITY HALL

102 Division St. ▪ P.O. Box 281 . Nome, Alaska 99762 . Phone (907) 443-6663 . Fax (907) 443-5345

WORK SESSION - 5:30 PM

A. Discussion of proposal on City involvement on the development of 3D housing in the City of Nome.

PAGE 2

White Paper - HUD Grant Proposal

R&D and Demonstration Project for 3D Concrete Printed Houses in Nome, Alaska

Project Description:

The following summarizes a proposal to the US Department of Housing and Urban Development ("HUD") for matching grant funding of $2 million in the aggregate ($1 million from HUD and a 50/50 cash match from the Denali Commission and the Alaska Housing Finance Corporation), to engage in a carefully crafted project by a team of industry and university experts to research, develop, demonstrate, test, and evaluate the viability of 3D Concrete Printing ("3DCP") as a faster, better, cheaper, and greener approach to meeting the need for affordable housing in rural Alaska than is currently possible with conventional construction.

The grant funds would be used to engineer, architect, design, and 3D concrete print two structurally sound, energy efficient, code compliant, move-in ready houses on parcels of land to be provided by the City of Nome, on site-appropriate foundations, using a 3DCP printer optimized for construction in rural Alaska, and using locally sourced sand, gravel, and rock as aggregate for the 3DCP construction material. In return for the City of Nome's contribution and support, the rights, title, and ownership of the two 3D-printed houses would transfer to the city at the completion of the project, to be used as they see fit.

Project Management and Participants:

The City of Nome, Xtreme Habitats Institute ("XHI"), and the Pennsylvania State University ("Penn State") will co-manage the project as a Research Partnership. Other participants in the project include the Cold Climate Housing Research Center ("CCHRC"), the Alaska Housing Finance Corporation ("AHFC"), the University of Alaska, Fairbanks ("UAF"), and X-Hab 3D, Inc.

Involvement by the City of Nome and XHI is critical because of their respective interests in meeting the need for affordable housing in rural Alaska. CCHRC, AHFC, and UAF's involvement is critical because of their cold climate expertise. Penn State's and X-Hab 3D's involvement in this project is critical because they have unique, industry-leading expertise in advanced materials and 3D concrete printing, which the other participants do not possess. Other entities expressing interest in participation include the US Army Corps of Engineers ("USACE") and the US Department of Defense Innovative Readiness Training Division ("IRT").

Background and Need:

The City of Nome, like most rural communities in Alaska, has a severe shortage of quality, energy-efficient, affordable housing. A significant portion of the existing inventory of affordable housing is characterized by dilapidation, over-crowding, energy-inefficiency, inadequate ventilation, and/or incomplete plumbing due to a lack of water and waste system infrastructure.

Increasing the availability of high-quality affordable housing is particularly challenging in rural Alaska. Rising costs of materials (e.g., lumber), shortage and cost of skilled labor, supply chain and transportation issues, one-off construction processes, and short building seasons make conventional construction too expensive and too slow to keep pace with Alaska's needs. 3DCP is a new, process-efficient technology that has the potential to produce similarly sized houses to those built with conventional construction, that are more durable and energy efficient, with cost and build time reduced by as much as 50% or more, using local geologic resources and eco-friendly additives for construction material.

Project Implementation:

Phase I of this Project includes:

- Engineering, architecting, designing (with input from local stakeholders), and 3D concrete printing of a structurally sound, affordable, energy-efficient, durable, and sustainable house on various types of foundations, depending on the ground, including permafrost, in Nome, Alaska.

- Developing an optimal concrete-composite 3D construction mixture that uses locally sourced sand, gravel and rock for the aggregate.

- Working with the City of Nome, AHFC, and other regulators to agree on acceptable standards for demonstrating residential building code compliance in Nome using 3DCP technology.

- Optimizing a 3D concrete printer with the requisite expeditionary capabilities, including mobility, closed-loop extrusion controls, precision printing, and position location, etc., for rural Alaska.

Phase II of this Project includes:

- Demonstrating this advanced construction technology by constructing two code compliant, move-in ready houses using 3D concrete printing and local sand, gravel and rock in the construction material, on suitable parcels of land provided by the City of Nome.

    - The main objective of the 1st house, to be 3D printed in Jul - Aug 2023, is to optimize the technique for on-site printing. The preferred site will have reasonably stable ground, to enable focus on optimizing the printed structure rather than the complexity of the foundation.

    - The main objective of the 2nd house, to be 3D printed in Jul - Aug 2024, will be to build on a site where permafrost is more of an issue, requiring a more complex foundation to ensure the long-term stability and structural integrity of the 3D printed house.

    - Development of use of lighter, stronger, and more flexible concrete-composite construction material.

    - Conducting long-term evaluation of the completed housing structures, using imbedded sensors and monitoring devices in both houses to monitor and evaluate their ability to meet rigorous structural, functional, and durability requirements through seasonal changes over time.

Construction / Design Parameters:

- 3BR / 1BA 1000 - 1200 sq.ft. Home
- Design Objective: Repeatable post Demonstration Cost < $300K
- Net Zero Carbon / Recyclable Building Materials
- High Star Energy Rating
- Healthy Ventilation System

- Healthy Water and Sanitation System
- 75+ year design life, built to withstand seismic, snow loads, permafrost freeze / thaw, wind

Timing:

- 7/22 – 5/23: Foundation, Design and Engineering, Advanced Materials, Printer Development
- 6/23 – 9/23: Shipping Printer and Equipment to Alaska, Construction of 1st House; Occupancy
- 9/23 – 5/24: On-Site and Remote Monitoring of All Aspects of 1st House
- 6/24 – 9/24: Construction of 2nd House; Occupancy
- 10/24 – Onward: Monitoring of Both Houses for Structural Integrity, Maintenance Requirements

How Will this Project Benefit the City of Nome:

- 3DCP has the potential to help solve the affordable housing crisis, building on advances in materials science, automation, and computing power. Proofs of concept are being deployed in markets worldwide and may revolutionize infrastructure development.

- The 3DCP houses to be constructed in Nome will be fully functional homes designed to meet the engineering requirements underlying the applicable residential building codes. If the project is successful, 3DCP could be used to meet significant housing shortages that exist in Nome and surrounding areas.

- 3DCP could also be used to meet the significant housing and infrastructure requirements that will be associated with the deep-water expansion of the Nome Arctic port.

- 3DCP could be much less expensive than stick-built; be more sustainable with the use of local geologic construction materials (moving away from traditional concrete with lighter, stronger more durable hybrids such as graphene, fly ash, iron tailings, lime, clay, etc.); more efficient - no waste; and much shorter construction time - from months to days.

- This project will be a beneficial opportunity for CCHRC, the University of Alaska, XHI, and AHFC to gain knowledge from Penn State in the area of 3DCP and advanced materials that Alaskan entities do not currently possess.

- Nome, rural Alaska, statewide, and all cold climate regions, will benefit from expanded knowledge in this field. Contributing to this body of work could realistically have a global impact if this technology revolutionizes the construction industry.

Risk Mitigation:

The project plans include a homeowner's warranty comparable to a traditional build, including the cost of any potential post-construction repairs to the housing structure. The project also includes 3DCP training for local trades and businesses. The project also includes a contingency for removal of the structures if they do not meet project objectives.

XTREME HABITATS INSTITUTE

OVERVIEW OF 3D PRINTING TECHNOLOGY FOR AFFORDABLE HOUSING CONSTRUCTION

JUNE 2022

Problem

- *Conventional construction can't keep pace with demand:*
  - *Too expensive (rising cost of materials)*
  - *Takes too long (labor intensive / shortages)*
  - *Too many job-related accidents*
  - *Builders avoiding lower end of the housing market because of lower profit margins*

Impact

- *Massive shortage of lower-end housing in US:*
  - *7M low-income homes*
  - *3.8M starter homes — a 50-year low*
  - *48M families can't afford med. priced house of $347K*
- *Massive need for new infrastructure in US:*
  - *$6T est. cost to repair US infrastructure (ACSE)*

Sources: NAHB, ACSE, Levelset, CICERO

Solution

3D Composite material Printing (3DCP):

A Paradigm Shift in Construction Technology

- Prints houses, buildings, prefab, and high-value structures with complex geometries
- >50% reduction in build time, labor and material costs, waste, and job-site injuries
- Uses locally available geologic resources for construction materials
- Enables rapid construction in extreme, isolated, difficult environments
- Use of advanced, functionally graded materials and movement away from cement

Example 3DCP Houses and Buildings


Oregon


New York


Virginia


Texas


Netherlands


Germany


Dubai


Dubai

3D Concrete Printing for Alaska

- *Expeditionary-grade Robotic Arm 3DCP printer*
- *Advanced (low-carbon, high strength) composite construction materials*
- *Design, engineering, printing, and support services*

Expeditionary Robotic Arm Printer

Designed for remote operation, without nearby infrastructure

Able to print in unimproved, challenging terrain

Set up and tear down without extra logistical support

Designed to utilize materials sourced locally

Leverages advanced digital tools for prefab visualization

Mobile platform for movement onsite and between sites

Can make printing adjustments in real time

Contact

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Item A.

sustainability

MDPI

Article

Environmental Footprint and Economics of a Full-Scale 3D-Printed House

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Abstract: 3D printing, is a newly adopted technique in the construction sector with the aim to improve the economics and alleviate environmental impacts. This study assesses the eco-efficiency of 3D printing compared to conventional construction methods in large-scale structural fabrication. A single-storey 3D-printed house was selected in the United Arab Emirates to conduct the comparative assessment against traditional concrete construction. The life cycle assessment (LCA) framework is utilized to quantify the environmental loads of raw materials extraction and manufacturing, as well as energy consumption during construction and operation phases. The economics of the selected structural systems were investigated through life cycle costing analysis (LCCA), that included mainly the construction costs and energy savings. An eco-efficiency analysis was employed to aggregate the results of the LCA and LCCA into a single framework to aid in decision making by selecting the optimum and most eco-efficient alternative. The findings revealed that houses built using additive manufacturing and 3D printed materials were more environmentally favourable. The conventional construction method had higher impacts when compared to the 3D printing method with global warming potential of 1154.20 and 608.55 kg CO_2 eq, non-carcinogenic toxicity 675.10 and 11.9 kg 1,4-DCB, and water consumption 233.35 and 183.95 m^3, respectively. The 3D printed house was also found to be an economically viable option, with 78% reduction in the overall capital costs when compared to conventional construction methods. The combined environmental and economic results revealed that the overall process of the 3D-printed house had higher eco efficiency compared to concrete-based construction. The main results of the sensitivity analysis revealed that up to 90% of the environmental impacts in 3D printing mortars can be mitigated with decreasing cement ratios.

Keywords: additive manufacturing; life cycle assessment; life cycle costing; sustainable construction; concrete

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1. Introduction

The construction sector is responsible for significant environmental stresses, consuming 48% of global supplied energy on an annual basis and depleting the natural resources [1]. In addition to exploitation of materials, manufacturing of construction materials and operational works are responsible for 38% of worldwide greenhouse gas emissions [2]. The sustainable development goals demand continuous monitoring of emissions and potential health risks of the implemented system. Understanding the environmental impacts of infrastructure and construction practices aids in developing efficient energy techniques. Moreover, low fatalities and injuries are common in the construction industry which encourages the automation of construction-related techniques. Furthermore, automation of construction activities is preferred to account for low productivity rates. More specifically, labour productivity, which is defined as construction workload expressed in units per man hour, plays a key role in the capital investment of the project as well as meeting the global housing demand [3]. Current rates of productivity combined with an increase in urbanization has been a concern in sustaining the increasing housing demand which is estimated to reach 230 billion m^2 in the next 40 years [4]. As a result, additive manufacturing has been proposed as an alternative to conventional construction. Additive manufacturing or 3D printing is being assessed as a potential solution to current methods of construction for energy reduction, automation of construction methods, mitigation of environmental impacts, and cost savings [2].

In addition to the consideration of materials, the construction industries face a continuous challenge of having to complete construction of the structures within the shortest time, while still having to maintain safety and work quality. Innovations in the construction industry have explored different techniques to account for the technical drawbacks and environmental impacts associated with conventional construction techniques. Automation of activities in the construction site have been proposed, particularly additive manufacturing or 3D printing technology, to improve construction practices [5]. The additive manufacturing process operates by continuously adding a layer-by-layer extrusion paste. It is also defined as a method of digitally fabricating materials via printers [6]. Each 3D printed layer is a 2D representation from the computer aided design (CAD) or building information modelling (BIM) model that is deposited to the printer [7]. Digital fabrication enables customization and assembly of complex designs. Attempts have been made to utilize 3D printing techniques in the construction industry and evaluate the sustainability and implications on the economic, environmental and social aspects [5]. A case study in China demonstrated the potential of large-scale 3D printing, whereby several houses approximately 200 m^2 have been built using high quality cement alongside glass fiber to enhance strength [8]. Another application represented the functionality of 3D printing by prefabricating the components of a 5 storey building and later assembled on site [9]. Wu et al. [7] asserted the importance of selecting appropriate material to attain the desired level of detailing and withstand the loading on the structure. A Complex design of a 12 m × 12 m × 12 m house with complex details has been successfully implemented using 3D printing [7]. The house was printed with glass reinforced plastic extrusion paste which was able to resist corrosion, aging and water seepage.

Digital fabrication foresees the potential of mitigating the environmental constraints and reducing the materials used in building sector [4]. Moreover, utilization of 3D printing technology in the construction industry can potentially lead to a reduction of energy supply and overall emissions up to 5% by 2025 in large scale projects (i.e., large filament size) [4]. The environmental performance of implementing additive manufacturing methods in the construction sector has been explored. Several studies investigated the environmental impacts of additive manufacturing in the construction industry using life cycle assessment (LCA) systematic framework. Sinka et al. [10] explored the environmental impacts of different 3D printing cement and gypsum binders. The results revealed that gypsum-based mixes had an overall reduction in GWP of 84% as a result of lower energy use. Other studies investigated the performance of different construction elements. Mrazović et al. [11] compared the environmental performance of conventional and 3D-printing of different metal building elements (such as steel frame and steel brackets). Additive manufacturing proved to be compatible for construction which achieved 40% lower environmental impact (compared to conventional manufacturing methods) [11]. Agustí-Juan et al. [12] utilized LCA to identify the viability of constructing walls with varying complexities using 3D printing compared to conventional construction techniques. The results revealed that complexity of structures did not increase the overall costs and the design of the structure was not responsible for environmental constraints as opposed to conventional building techniques. Moreover, the literature has been focused on studying the environmental impacts particularly, climate change potential and energy consumption as they have been reported to have the greatest effects [13]. The climate change impact of conventional walls was 75%, whereas the 3D-printed wall had negligible impact (2%). Climate change was reported to have significant environmental impacts as a result of the GHGs emissions during the material production, manufacturing, transport and construction phases [12]. Another case study assessed the environmental impacts from the materials production and operation of 3D-printed wall and roof structures [14]. Results highlighted the minimal impacts of operation of fabrication robots, while the mainstream energy consumption originates from material production. Mohammad et al. [15] also investigated the environmental performance of 3D printed walls compared to conventional reinforced concrete ones. The 3D concrete printing (3DCP) scenarios yielded lower emissions in terms of global warming potential and acidification potential. The study further combined conventional reinforcement with 3DCP, and the environmental impacts were still lower than conventional construction techniques.

All of the above mentioned studies only assessed the environmental impacts of different structural elements, on the other hand, Han et al. [16] developed a 3D model simulating a 3D-printed house. The emissions were calculated using equations from the literature. The findings of the study revealed that construction using 3D printing technology resulted in higher emissions when compared to cast in-situ conventional concrete. Moreover, the study attributed the high emissions to cement production processes. Another study compared the environmental impacts of 3D printing and conventionally built house [17]. The study utilized concrete and cob (a sustainable material) to run the analysis. The 3D printing technology acquired lower impacts compared to conventional concrete construction. In terms of materials, cob attained lower impacts, nevertheless, 3DCP binder consumed less energy. In terms of economic viability, a case study in the United Kingdom investigated the financial feasibility of 3D printed residential structures using life cycle costing analysis (LCCA). The findings of the study revealed savings up to 35% when compared to conventional houses due to lower material consumption and eliminated labour cost [18].

Conventional construction is responsible for significant environmental and safety risks which compels introduction of new efficient and feasible alternatives. Digital technologies, particularly 3D printing, have been successfully implemented in the field of construction. Evaluation of the systems encompasses quantification of environmental impacts using the standard LCA tool and economic value of building structures using conventional manufacturing methods versus 3D printed methods. The capital and energy costs incurred over the life cycle of the examined structural systems are estimated using life cycle costing analysis. An eco-efficiency analysis is used to combine the results of the LCA and LCC into a single framework to assist decision makers with the choice of the optimum construction method taking account the environmental and economic perspectives. A search of recent publications (Table 1) in this field showed that most of the studies focus primarily on developing the 3D printing mortar and utilizing sustainable materials. The literature lacks comprehensive and integrated environmental and economic assessment of large-scale 3D printed buildings. Since this technology is under development, more studies are needed to optimize the materials and methods used from both environmental and economic perspectives. This study aims to enrich the literature with comprehensive assessment of such a knowledge base which is essential to drive the shift towards digital fabrication construction. This study provides a comparative assessment of a 3D-printed structure compared to conventional concrete construction. The comparative assessment is applied on an actual single-storey house located in Dubai, United Arab Emirates (UAE).

Table 1. Summary of life cycle assessment-based studies in the construction sector.

References	Boundary	3D-Printed Unit	Stages	Impact Assessment Method	Software	Database	Functional Unit	Evaluated Impacts
[6]	-	Hypothetical house model	Material acquisition; construction Phase	Building Life-cycle Sustainability Impact Assessment Standard	-	Local data; Literature review	1 m^2 wall; 1 m^2 roof	Global warming potential; Acidification; Photochemical Pollution; Eutrophication
[10]	Cradle to gate	Cube Samples	Production	IPCC 2013 GWP100a	SimaPro 8	Ecoinvent 3; Previous studies	1 m^3 binder	Global warming potential
[15]	Cradle to gate	Wall structure	Production; Construction	TRACI	GaBi 9.2.1.68	GaBi 2020	1 m^2 external load-bearing wall	Global warming potential; Acidification potential; Eutrophication potential; Smog formation potential; Fossil fuel depletion
[17]	Cradle to Site	One-storey house	Raw materials; Transportation; Construction	ReCiPe Midpoint (H) v1.03	SimaPro 9.0.0.35	Ecoinvent v3.1; Literature; Local data	1 m^2 load-bearing wall	global warming; Stratospheric ozone depletion; Fine particulate matter formation; Marine eutrophication; Land use; Mineral resource scarcity; Water use
[11]	-	Metallic building components	Raw material processing; Manufacturing; Transportation	-	SimaPro	Local data	1 steel bracket	Energy consumption; Human health; Water source depletion; Abiotic depletion of fossil fuels
[12]	Cradle to gate	Wall Structure	Raw material extraction; Transport; Materials production; Robotic fabrication	Recipe Midpoint (H) v1.12	SimaPro 8	Ecoinvent v3.1	1 m^2 of wall	Climate change; Ozone depletion; Human toxicity; Terrestrial acidification; Freshwater eutrophication; Terrestrial ecotoxicity; Freshwater ecotoxicity; Water depletion; Metal depletion; Fossil depletion
[2]	Cradle to grave; Cradle to gate	Wall and roof structures	Materials production; Operation energy	Recipe Midpoint (H) V1.06	SimaPro 8	Ecoinvent v2.2	1 m^2 of wall and roof structures	Climate change; Ozone depletion; Human toxicity; Water depletion; Metal depletion; Fossil depletion

2. Methodology

In this section, the structural system components and configurations were discussed, followed by a description of the 3D printing technology utilized to construct the house understudy. Moreover, the standard methods of the environmental and financial life cycle analyses were presented.

2.1. Structural Systems

A single-storey detached house located in the UAE was selected as a case study. Figure 1 shows the plan and elevation layouts of the selected house with a net floor area of 90 m^2 and total height of 4.5 m. The proposed structural systems include (1) conventional construction method using cast in place concrete walls and flat slab with beams and columns, and (2) additive manufacturing using self-reinforced printable mortar. It should be noted that the construction time frame of the 3D printed house was approximately 2 weeks, whereas the conventionally built house was 4 months based on local engineering contractors. The timeframe excludes the HVAC, plumbing, and finishes works as they are similar in both houses.

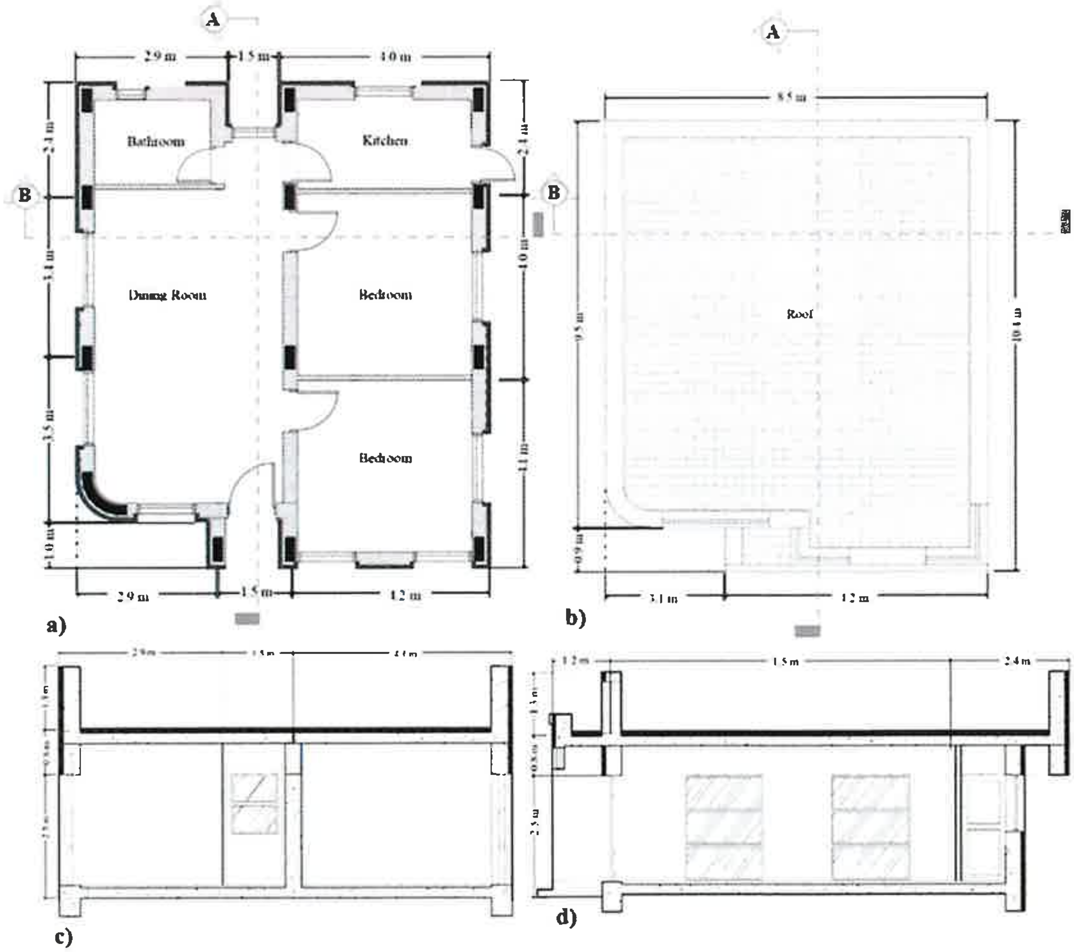

Figure 1. The technical drawings for (**a**) ground floor, (**b**) Site plan, (**c**) section A, and (**d**) section B.

Table 2 shows the details of the structural elements utilized for conventional concrete construction. The columns and beams have a cross-sectional area of 800 and 1600 cm^2, respectively, whereas the slab has a total area of 376 m^2. Wood formwork was utilized in construction of the columns, beams, and slabs of 3.8 m^2, 47 m^2, and 400 m^2, respectively.

There are 0.03, 0.04, and 0.245 m^3 of columns, beams, and slabs per m^2. The design of the steel reinforcement, confinement steel, and stirrups were conducted according to American Concrete Institute (ACI) standards [19]. Moreover, the considered primary loads in this study were the typical dead and live loads defined by American Society of Civil Engineers (ASCE) 7–10 [20].

Table 2. Dimensions and reinforcement of structural elements.

Element	Component		Value
External Wall	Specifications	Length (m) × Height (m)	37.8 × 2.95
		Required concrete (m^3)	6.19
		Total concrete bricks	15,478
Column	Specifications	Length (cm) × Width (cm) × Height (cm)	40 × 20 × 295
		Total number	13
	Reinforcement	Rebar size	10
		Spacing (cm)	25
		Total cross-sectional area (cm^2)	20.5
Beam	Specifications	Length (cm) × Width (cm)	40 × 40
	Reinforcement	Rebar size	22
		Number of rebars	6
		Total cross-sectional area (cm^2)	23.22
Slab	Specifications	Slab depth (cm)	0.25
	Reinforcement *	Rebar size	10
		Spacing (cm)	20
		Total number of main reinforcements	78
		Total number of secondary reinforcements	95

* The design details include main and secondary reinforcing rebars.

The specifications and properties of the cementitious mortar used for conventional concrete and 3D printing mixtures are summarized in Table 3. The conventional concrete mix has cement, sand, and aggregates ratio of 1 to 1.5 to 1.3, respectively, while the cementitious 3D printing mortar consists of 70% sand and 30% binder (cement and additives) [21]. Moreover, the mix of the 3D printing mortar is characterized by low sulphate and chloride content which was designed for structural and non-structural elements.

Table 3. Properties of 3D printing and conventional construction materials *.

System	Components *	Specifications
Conventional Concrete **	Ultimate Compressive Strength (MPa)	35
	Water/cement Ratio	0.5
	Maximum Aggregate Size (mm)	20
	Slump (mm)	20–80
	Mixing Water (kg/m^3)	200
	Density Concrete (kg/m^3)Vt	2355
3D Printing Mortar *	Grain Size (mm)	3
	Initial Set (min)	3
	Final Set (min)	5
	Layer Thickness (mm)	40
	Ultimate Compressive Strength (MPa)	40
	Tensile Strength (N/mm^2)	4
	Flexural Strength (N/mm^2)	6
	Specific Heat Capacity (J/g·K)	1.1
	Air Void Content (%)	5.3

* Compiled from [21] and ** [22].

2.2. *Additive Manufacturing Technology*

The application of a large-scale 3D printed structure entails using an extrusion method, in which the structure was built by adding layers of the prepared mortar through a nozzle. The digital STL (STsereo Lithography) formatted file was converted into several 2D layers by means of CyBe CHYSEL software [21]. Moreover, Table 4 summarizes the input parameters required for the operation of the mobile 3D printer. Furthermore, the printing process was regulated through a control unit which operates the mixing system to pump the mortar through a hose into the robotic arm. The mortar was added layer by layer at the specified coordinates via a 40 mm nozzle. The 3D printing filaments were characterized by a zigzag pattern and the printed walls were hollow (39 cm).

Table 4. Operating parameters of the 3D printer used.

Parameter	Value
Print Speed (mm/s)	50–600
Travel speed (km/h)	3
Precision (mm)	1:1:1
Layer resolution (mm)	10–50

2.3. *Life Cycle Analysis*

The environmental impacts and burdens on the ecosystem of production, construction, operation, and disposal stages over the life cycle of a system was quantified using the LCA systematic framework. The international organization for standardization (ISO) developed ISO 14044 and ISO14045 to unify the approach of evaluating the load on the environment, address the resulting ecological impacts and identify potential performance enhancement over the lifecycle of the systems [22,23]. Two LCA approaches are commonly investigated in the construction industry, namely, cradle to grave and cradle to site. The first method includes all materials and processes in a comprehensive assessment, while the second approach focuses on certain aspects of the construction project such as the materials [17]. In this study, a cradle to site approach was selected and the LCA was performed in four stages including, goal and scope, life cycle inventory (LCI), and life cycle impact assessment (LCIA) analysis, and results interpretation. Stage one of the LCA involves defining goal and scope as well as the system boundaries and functional unit. The LCI phase includes collection of data, while the third sage (LCIA) examines the contribution of these data to selected impact categories. Stage 4 involves assessment of the results and identifying study limitations. SimaPro 9.0 developed by PRé Sustainability was utilized to implement the LCA framework using Ecoinvent 3.0 [24].

2.3.1. Goal and Scope Definition

The goal of this study is to evaluate the environmental performance of a 3D printed house compared to conventional construction techniques. Measuring the functionality of both construction techniques output was achieved by selecting a reference or a functional unit; 1 m^2 of the single-storey house surface area was selected for simplification of inventory data calculations. Figure 2 shows the boundaries of the examined systems including, production and manufacturing of materials, construction, operation, maintenance, and end of life phase. However, the LCA assessment was limited to material extraction, construction, energy consumption, and transportation during the operation phase. Similar components in both structural systems were excluded i.e., earthworks, HVAC systems and finishes. The labour and end of life phase were excluded from the study as they were found negligible [17]. Moreover, all of the reviewed literature (Table 1) excluded the end of life or demolition phase as a result of lack of available data.

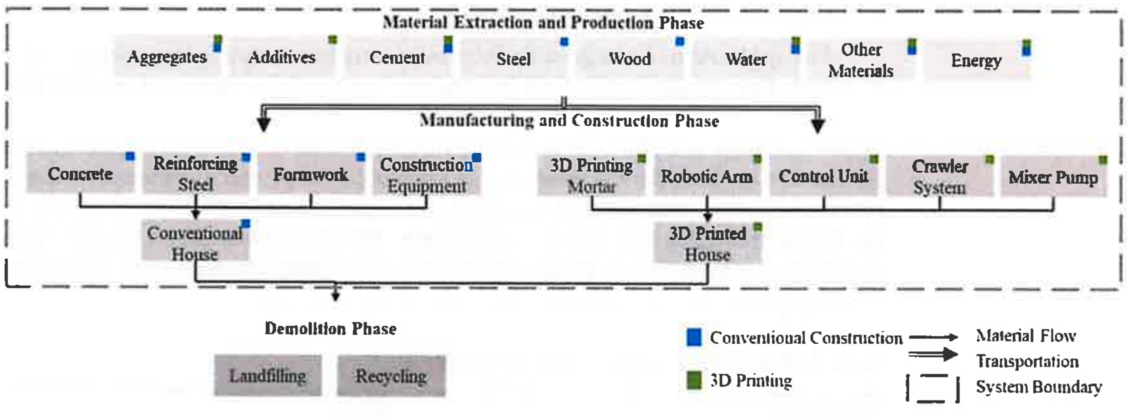

Figure 2. System boundaries of 3D printing and conventional construction of the examined house.

2.3.2. Life Cycle Inventory

The input data related to 3D printing and conventional construction were gathered from local suppliers, Ecoinvent database and the literature. Such technical data include foreground components such as quantity of materials, transportation, and energy consumption. Moreover, background data of the environmental burdens were assigned to the foreground processes and components. Table 5 lists the inventory data of the examined structural systems, in which energy consumption of the equipment utilized on-site can be measured from the power demand and operation time of such machinery.

Table 5. Life cycle inventory data of the examined systems per functional unit.

Data	3D Printing *	Conventional Construction **
Steel (kg) ***	-	200
Fly Ash (kg)	170	-
Micro silica (kg)	180	-
Superplasticizer (kg)	10	-
Viscosity modifying admixture	98,103	-
Cement (kg)	430	300
Coarse Aggregate (kg)	-	4680
Fine Aggregate (kg)	645	4680
Water (kg)	180	190
Concrete (kg)	-	340
Wood (m^2)	-	5
Energy Consumption (kWh)	21	68 ***
Material Transportation Distance (km)	100	100
Printer Transportation Distance	6500	-

* [25] ** [2,26] *** [27].

2.3.3. Energy Consumption

The energy consumption rates in the construction sector reach up to 40% of the total energy demand [28]. The primary electricity consuming sources are the cooling systems as a result of the harsh climate of the UAE with temperatures reaching up to 48 °C, hence the construction sector is constantly exploring efficient heat insulating materials to prevent overheating and humidity increase. The European commission has reported that buildings are responsible for at least 40% of the total energy consumption Particularly, air conditioning is a major energy consuming element in a building, hence reduction of cooling load demand by thermal insulation through construction materials inducing low heat transfer can save up to 50% of the building energy demand [29]. The energy savings for the 3D-printed and conventional concrete house were calculated based on the difference between the microclimate and the air temperature surrounding the structure as well as the thickness of the structural elements (external walls and roof). The ISO standard (EN ISO 6946:2008) reported the key factor to indicate the thermal properties of the building is heat transfer (U) in which lower U-value indicates higher energy savings [30]. The U-value [31] and the energy transfer or heat flow (Q) [32] were calculated using Equations (1) and (2) [33,34]:

$$U = \frac{k \times A}{l} \tag{1}$$

$$Q = \Delta T \times U \times A \tag{2}$$

where U is the thermal transmittance ($W/m^2{\cdot}K$), k is the thermal conductivity of a material ($W/m{\cdot}K$), A is the plane area of (m^2), l is the thickness of material (m), Q is heat flow (W), and ΔT is the temperature difference between external and internal structural element surface (°C). The heat transfer through individual rooms of the house, the windows, and doors was calculated. The design temperature outside and inside the house was specified by local guidelines as 46 °C and 24 °C, respectively. Moreover, the U-value of the floor and roof slabs were obtained from local standards and they were compared to ASHRAE (American society of heating, refrigerating and air-conditioning engineers) specifications based on perimeter to area ratio and thermal resistance values [33,34].

2.3.4. Life Cycle Impact Assessment

The environmental impacts of the digitally fabricated and conventionally built house were estimated using ReCiPe 2016 V1.03 midpoint (H) indicators [35]. The method represents the impacts of a global representative and addresses 18 different categories. The impact mechanisms include climate change or global warming potential (kg CO_2 eq) ozone layer depletion (kg CFC-11), terrestrial acidification potential (kg SO_2), marine eutrophication (kg N), freshwater eutrophication (kg P), human toxicity (kg 1,4dichlorobenzeen), particulate matter formation (kg PM2.5), ionizing radiation (kBq Cobalt-60), photochemical oxidant formation (kg NMVOC), terrestrial, freshwater, and marine ecotoxicity (kg 1,4dichlorobenzeen), agricultural and urban land occupation (m^2), freshwater depletion (m^3 water consumed), mineral resource depletion (kg Copper (Cu)), and fossil fuel scarcity (kg oil) [35]. The impact categories represent the effect on the environment and are based on weighted and normalised factors [36].

2.4. *Life Cycle Costing Analysis*

The financial viability of 3D printing and conventional construction techniques was investigated by calculating the construction and energy use costs. The capital cost of the examined projects included procurement and manufacturing of construction materials e.g., cement, steel, wood, aggregates, and admixtures, as well as construction activities. The present value (PV) of the electricity costs of the systems was estimated for a period of 50 years, which was carried out via LCCA framework to estimate the present worth of the energy consumed in the 3D printed and conventionally constructed house. Moreover, the time value of the cashflow was considered in this study using a local-based discount rate of 3% [37]. Equation (3) is used to calculate the present value [38]:

$$PV = \sum_{t=1}^{T} C_{o,t}(1+r)^{-t} \tag{3}$$

where C_o is the cash outflow (USD) of year t, r is the discount rate (%), and T is the lifespan of the project.

2.5. *Eco-Efficiency Analysis*

Selection of an optimum alternative and identification system trade-offs can be accomplished through an eco-efficiency analysis. Such analytical framework functions by agglomerating LCC and LCCA results, which are plotted into a single portfolio [23]. The

Item A.

ratio method is the most commonly used approach to determine the eco-efficiency of a system or a product [39–41]. In this study, the ratio method was employed which is defined as the ratio of economic indicator to environmental performance of the examined system as shown in Equation (4) [41].

$$\text{Eco} - \text{efficiency} = \frac{\text{Environmental Performance}}{\text{Economic Value}} \quad (4)$$

The Environmental indicator in this research study was retrieved from the LCA SimaPro software represented by a normalized and weighted single value aggregating all the midpoint categories. Moreover, the present value was utilized which corresponds to the economic indicator of each assessed system. An eco-efficiency portfolio combining environmental and economic scores was plotted for the selection of the most eco-efficient system and assessing the trade-off among the studied alternatives.

3. Results and Discussion

3.1. Environmental Analysis

The LCA results analysed in this section represent a comparison of additive manufacturing and conventional construction techniques in terms of the environmental impacts. The environmental impacts of the studied scenarios were calculated via SimaPro in 4 stages—characterization, damage assessment, normalization, and weighing [24]. During the first stage (characterization), the materials were multiplied by a factor that represents the relative contribution. The damage assessment facilitates the use of endpoint categories, where impacts with the same units can be added. Normalization stage enables comparison among scenarios in which the impacts are divided by a reference. The weighing phase is typically performed by multiplying the impact categories with a factor and adding them to result in a single score. This score is an indication of the total impacts. Table 6 provides detailed environmental performance scores for each impact category of the 3D-printed and concrete-based house. Most impact categories had significantly higher values for the conventional construction method. Among the highest scored impacts in the conventionally built house were global warming, non-carcinogenic toxicity, water consumption, carcinogenic toxicity, and fossil resource scarcity. Cement production contribution to global warming potential (1154.2 kg CO_2 eq) was approximated to be 70%. Moreover, reinforcing steel production and manufacturing comprised 98 and 97% of the total emissions of non-carcinogenic and carcinogenic toxicity with relative impact of 675 and 169 kg 1,4-DCB, respectively. Furthermore, fossil scarcity (150 kg oil eq) was attributed to the manufacturing of steel (60%) and cement (38%), and the high-water consumption was mainly due to addition of water during concrete manufacturing. The Global warming potential and water consumption had relatively high impacts for the 3D-printed house. As for the concrete constructed house, global warming potential (609 kg CO_2 eq) was high due to production and manufacturing contributing 97% and water consumption with a volume of 184 m^3 per functional unit was attributed to water demand during 3D mortar preparation. The endpoint indicators were represented by a single score that combines all the inventory results in one factor. For the 3D-printed and the conventional house, the human health category had substantially higher impacts compared to effect on ecosystem and natural resources indicators. Human health category caused 93 and 88% of overall emissions of the conventional construction and 3D printing scenarios, respectively.

The obtained results from SimaPro were normalized and weighted to provide holistic assessment. Normalization enables for a coherent interpretation of the characterized environmental impact categories through referring to a reference scheme, followed by weighting which emphasizes the relative significance of the impact indicators. Figure 3 shows the relative environmental impacts of the examined systems analysed based on different impact categories. It is evident that 3D printing has an overall lower impact across all categories. The 3D printing scenario performed more than 50% better for the majority of the categories which may be attributed to the material efficiency compared to the conventional scenario. Typically, conventional building requires formworks and reinforcing steel, which are absent in the 3D printing scenario. Therefore, all emissions related to the production, manufacturing, transportation, and fabrication of materials are reduced. The damage to the ecosystem was minimal where the midpoint categories pertaining to freshwater marine, and terrestrial species had relatively low percentage (0–7%). Though all categories of 3D printing had lower impacts, the water consumption category was only 20% better for the 3D printed house due to high water use during cement production processes and electricity generation, which is common to both construction methods.

Table 6. Environmental inventory results of the examined structural systems.

	Impact Category	3D Printing	Conventional Construction
Midpoint Indicator	Carcinogenic Toxicity (kg 1,4-DCB)	4.30	168.60
	Fossil Resource Scarcity (kg oil eq)	2.90	150.00
	Fresh Water Ecotoxicity (kg 1,4-DCB)	0.23	23.90
	Fresh Water Eutrophication (kg P eq)	0.002	0.20
	Global Warming (kg CO_2 eq)	608.55	1154.20
	Ionizing Radiation (kBq Co-60 eq)	2.58	16.50
	Land Occupation (m^2a crop eq)	0.40	6.80
	Marine Ecotoxicity (kg 1,4-DCB)	0.34	33.60
	Mineral Resource Scarcity (kg Cu eq)	0.08	30.80
	Non-carcinogenic Toxicity (kg 1,4-DCB)	11.9	675.10
	Ozone Depletion (kg CFC11 eq)	1.90×10^{-4}	3.20×10^{-4}
	Particulate Matter Formation (kg PM2.5 eq)	0.02	1.70
	Photochemical Oxidant Formation (kg NO_x eq)	0.06	2.84
	Terrestrial Acidification (kg SO_2 eq)	2.50	4.10
	Water Consumption (m^3)	183.95	233.35
Endpoint Indicator	Human Health (Pt)	5.30	18.63
	Ecosystems (Pt)	0.64	1.30
	Resources (Pt)	0.05	0.20

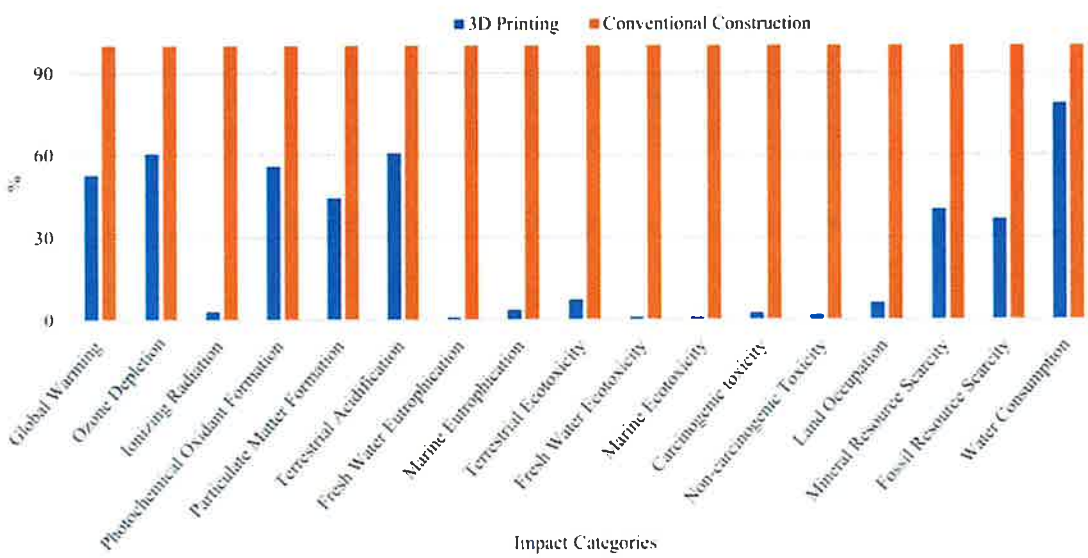

Figure 3. Relative environmental impacts of 3D printed and conventional constructed houses.

In the digitally fabricated house, cement production phase contributed (more than 95%) to most of the impact categories i.e., global warming, ozone depletion, terrestrial acidification and ecotoxicity, human carcinogenic impacts, and fossil and mineral resource scarcity as shown in Figure 4. Moreover, material extraction and production of the utilized admixtures was a major contributing process to land occupation, freshwater eutrophication, ionizing radiation, marine and freshwater ecotoxicity, and non-cariogenic human effects, with 99, 98, 97, 61, and 40%, respectively. Electricity and transportation obtained the lowest ratio in all environmental impact categories with impacts ranging between 0 to 2%.

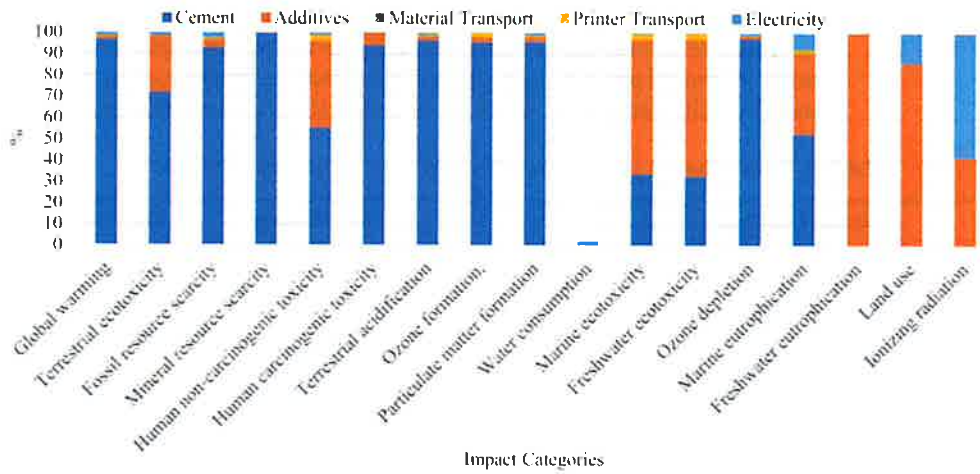

Figure 4. Contribution of 3D printing processes to the overall environmental impact.

The contribution of the different impacts i.e., production of cement and steel, manufacturing of concrete, transportation, as well as electricity production are shown in Figure 5. The cement production shows the highest contribution in all impact categories due to significant consumption of raw materials and energy, the greenhouse gas emissions during manufacturing phase, and the release of bulk amounts of waste. Moreover, the environmental analysis revealed that reinforcing steel production and manufacturing processes had a primary impact on freshwater eutrophication (99%), land occupation (98%), terrestrial and marine ecotoxicity (93%), carcinogenic, non-carcinogenic and freshwater ecotoxicity (89%), fossil resource scarcity (60%), and global warming (41%). Similar to the conventional house results, the electricity scored the lowest in all categories except ionizing radiation (11%). Overall, the exploitation of materials, energy use, and transportation during manufacturing of concrete components poses the highest environmental risks as can be deduced from Figure 5.

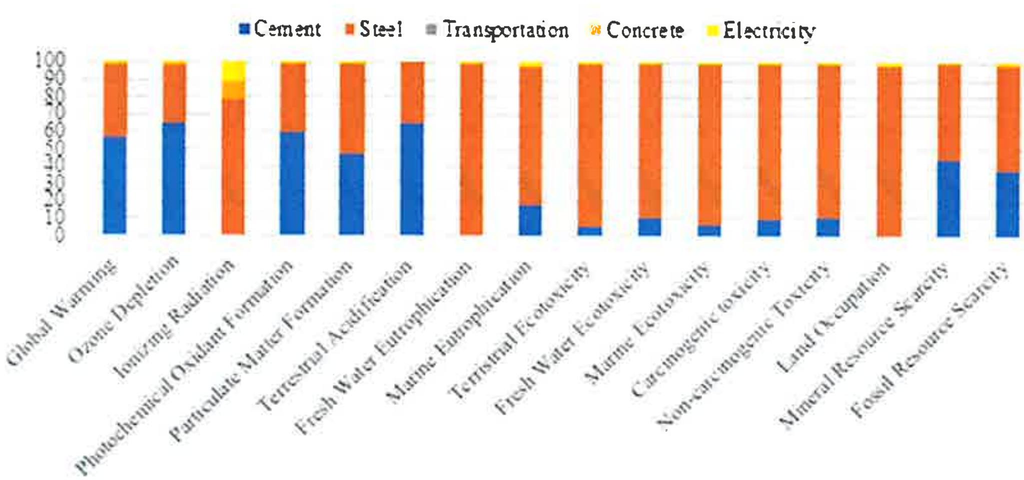

Figure 5. Relative contribution of conventionally constructed house processes to the environmental impact.

The results of this study agree with the outcomes of [2,12,17], which reveals that 3D printing structures outperform the conventional construction methods in terms of overall environmental impacts. The main difference in this study was conducting the analysis for the entire house, whereas [2,12] studied the impacts on individual elements (wall, roof, and a concrete slab) with varying design complexities and included the operation phase for the self-shading wall element. Moreover, the 3D printing mortar ratios and components in this study was tested for an implemented project in the UAE, while Agustí-Juan and Habert [2] adopted a fiber reinforced concrete from the literature and Alhumayani et al. 16 tested out three different mixes also compiled from the literature and compared the results. Furthermore, Agustí-Juan et al. [12] designed a high performance 3D printing concrete which was found to increase the GHG emissions when compared to conventional concrete mix.

3.2. Operational Energy

The cooling energy demand for the 3D-printed and conventionally constructed house was calculated considering the thermal transmittance of the construction mortars. Table 7 summarizes the cooling systems calculation results for the 3D-printed and conventionally constructed house. Overall, the total heat transfer (gain) of the conventional building system was 5% more than the 3D printed house. The 3D printed house acquired less heat gain due to higher material thickness and thermal transmittance (K). In other words, the lower thermal conductivity and thickness of materials the lower heat transmission. Another contributor to low heat conduction is U-value, where the slabs of a 3D-printed house had lower U-values compared to the conventional concrete house. On the other hand, the insulating properties of the 3D-printed wall including an air cavity had a much higher U-value (3.75 W/m^2·K) which is in close proximity to the concrete wall (3.6 W/m^2·K).

Table 7. Insulation parameters and cooling demand results.

Parameter	3D Printing						Conventional System					
	Wall				Floor	Roof	Wall				Floor	Roof
K (W/m·K)	0.92						0.55					
R (m^2·K/W)	0.08				0.33	0.16	0.09				0.46	0.45
Thickness (m)	0.08				0.3	0.15	0.05				0.25	0.25
U (W/m^2·K)	3.75 *				0.27	0.10	3.6 *				0.44	0.44
Q (W)	W1 2189	W2 3424	W3 3123	W4 2783	201	519	W1 2157	W2 3374	W3 3077	W4 3742	858	858
Σ Q ** (BTU/h)	49,269						52,098					

* The wall U-value includes air cavity with thickness 0.04 m and R of 0.12. ** The total heat gain includes heat from doors and windows.

3.3. Economic Assessment

The economic analysis findings of the selected structural systems are summarized in Table 8. The results comprise capital costs of materials (local-based) including civil works and operational expenditures of cooling systems. The conducted present value over a 50-year design period indicates that conventional construction technique was the most expensive alternative (USD81,064) which was double the cost of the 3D printing. This can be attributed to the cost of concrete, and formworks which comprise 51 and 24%, respectively. The capital expenditures of concrete are associated with the purchase and manufacturing of various sub-components, mainly aggregates (USD10,795). Although the steel cost rate (USD500/ton) was the highest, it had the least contribution to the overall cost. On the other hand, the 3D printing technology was found to be 49% cheaper than the conventional construction scenario. The 3D printing excludes multiple aspects including construction components, e.g., concrete and formworks, as well as labor cost, thus reducing the overall capital costs. These results are in line with [18], where the 3D printing of houses contributed to 35% savings compared to conventional construction.

Item A.

Table 8. Capital costs of construction components and operational expenses.

Component	Rate (USD/ton)	3D Printing	Conventional
Cement	15	45	44
Additive	220	8	-
Aggregate	15	10,795	10,795
Steel	500	-	1308
Concrete	$60/m^3$	-	25,147
Formwork	$27/m^2$	-	11,933
Present Value (USD)	-	**−40,955**	**−81,064**

Note: Positive present values signify revenues, whereas negative values represent costs.

4. Eco-Efficiency Analysis

The depicted results of economic and environmental performance ratios were plotted in an eco-efficiency portfolio as illustrated in Figure 6. The top-right corner distinguishes the low eco-efficiency alternative, while the bottom left corner of the plot area identifies the high eco-efficiency option. The conventional construction house had significantly lower eco-efficiency compared to 3D-printing. Upon comparing the operation phases of both houses, the results reveal similar eco-efficiency scores, which coincides with the LCC and LCA analyses. Moreover, the eco-efficiency index diagram orders the alternatives from the highest (bottom) to lowest (top) eco-efficiency. The 3D printing method was found to be the highest and conventional construction acquired the lowest eco-efficiency. The findings of eco-efficiency analysis showed that operation phase alone was negligible in the selection process of the optimum alternative, nevertheless the combined construction and operation phase revealed 3D-printing as the most eco-efficient option.

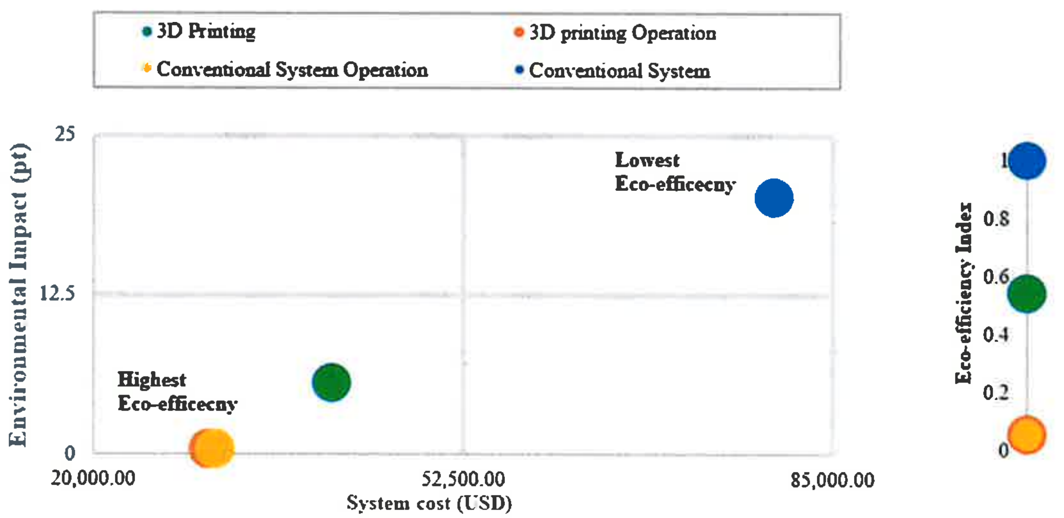

Figure 6. Eco-efficiency portfolio of 3D-printed and concrete-based house construction and operation phases.

5. Sensitivity Analysis

Several factors such as system boundaries, assumptions, and accuracy of inventory data affect the certainty of LCA and LCC results. Moreover, the 3D printing technology is still in the exploration and development stage and the data were compiled from the literature. A sensitivity analysis was conducted to account for the uncertainties in this study where the selected parameters are listed in Table 9. Different 3D printing binder mixtures were evaluated in the analysis to investigate the environmental impact of cement and coarse aggregates as they acquired the highest scores in the LCA results. The conventional concrete mix was also evaluated to investigate the effect of varying concrete and steel quantities [2,42].

Table 9. Parameters utilized in the sensitivity analysis for 3DCP and Conventional scenarios.

Parameter		Reference Value		Sensitivity Analysis Options			
		3D Printing	Conventional	3D Printing *		Conventional	
				Mix 1	Mix 2	Mix 1 **	Mix 2 ***
Life Cycle Analysis	Steel (kg) ***	-	200	-	-	560	61
	Fly Ash (kg)	170	-	165	165	-	-
	Micro silica (kg)	180	-	83	83	-	-
	Superplasticizer (kg)	10	-	8.3	8.3	-	-
	Viscosity modifying admixture	98,103	-	98,103	98,103	-	-
	Cement (kg)	430	300	580	300	53	10
	Coarse Aggregate (kg)	-	4680	1241	64	1135	1280
	Fine Aggregate (kg)	645	4680	-	-	-	2
	Water (kg)	180	190	232	190	231	822
	Concrete (kg)	-	340	-	-	7	140
	Brick (kg)					197	-
	Wood (m^2)	-	5	-	-	77	25
	Energy Consumption (kWh) ****	21	68	2.26	2.26	11	18
Life Cycle Costing	3D Printer (USD)	183,000	-	-	-	-	
	Electricity Tariff (USD/kWh)	0.081		0.07–0.101			

* Adapted from [15] ** [2], and *** [42], **** The energy consumed by machinery.

The concrete, steel, and cement production accounted for the highest environmental scores in the performed LCA. Figure 7 illustrates the results of the sensitivity analyses for the different 3DCP and Conventional mixtures. The results are presented relative to the conventional base scenario which obtained the highest impacts in all categories. The analysed mixtures had relatively small impacts contributing to 0–3% in all categories. Nevertheless, the 3DCP mix 1 and 2 contributed to the highest water consumption (474 and 391 m^3, respectively), followed by conventional mix 1 (390 m^3), conventional base scenario (233 m^3), the 3DCP base scenario (184 m^3), and the least water consumption was attained by conventional mix 2 (110 m^3). These results led to the conclusion that reducing cement quantities in 3DCP binder can reduce the overall environmental impacts by 90%. In conventional construction techniques replacing some concrete elements with bricks (such as conventional mix 2) can also reduce the environmental deterioration.

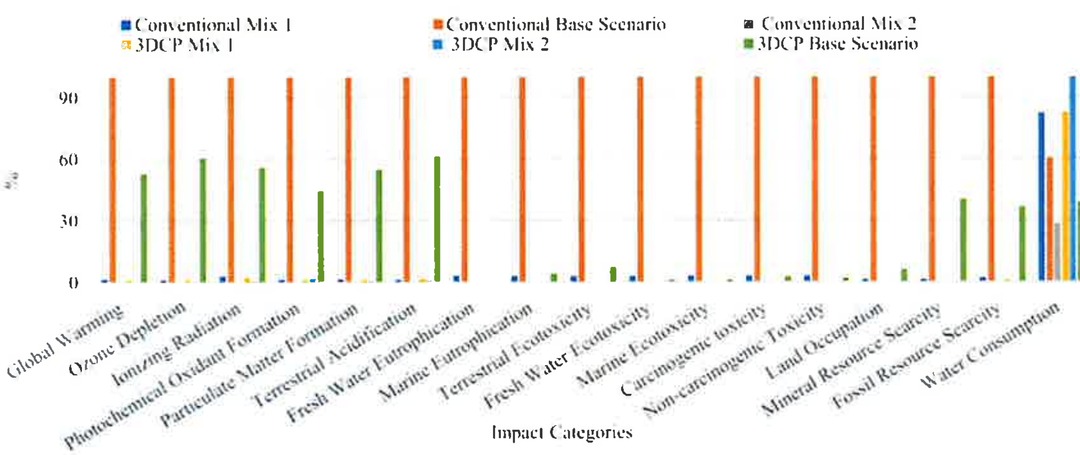

Figure 7. Sensitivity analysis results of different conventional and 3D concrete printing (3DCP) mixtures.

The LCC results of the different mixtures reveal significant differences from the original scenarios (Table 10). The 3DCP mix 1 and 2 showed almost similar results with a decrease of 20% from the original mix. This decrease can be attributed to the reduction of cement in mix 1 and mix 2. Conventional concrete mixtures 1 and 2 obtained a total cost of USD 33,073 and 31,451, respectively which is almost 60% less than the base scenario. Moreover, the cost of the 3D printer was added to the 3D printed house scenario while keeping all the other parameters constant. The present value was found to be USD 225,391 (82% increase in expenditures). Since the technology is still in the exploration stage, a renting cost is yet to be accounted for in future 3D construction projects. Different electricity tariffs ranging between 0.07 to 0.1 were investigated. For low electricity tariffs, the costs of the 3D printing scenario decreased by 5% and increased up to 25% for higher ranges. Similarly, the costs of the conventional scenario decreased by 7% and increased up to 7% for higher ranges.

Table 10. Life Cycle Costing of the different sensitivity analysis alternatives.

Sensitivity Analysis Options		Present Value (USD)
3DCP Mix 1		−32,664
3DCP Mix 2		−32,588
Conventional Mix 1		−33,073
Conventional Mix 2		−31,451
3D Printer		−225,391
Electricity Tariff	3DCP	−38,972 to −51,427
	Conventional	−75,741 to −87,483

Data uncertainty and limited availability typically affects the life cycle assessment results. Figure 8 shows a +10% variation of the LCC and LCA parameters studied in the current research. The figure revealed a correlation of operation of both 3D printed and conventional scenarios. Nevertheless, the construction of conventional system had the greatest environmental impact and greatest cost with the variation.

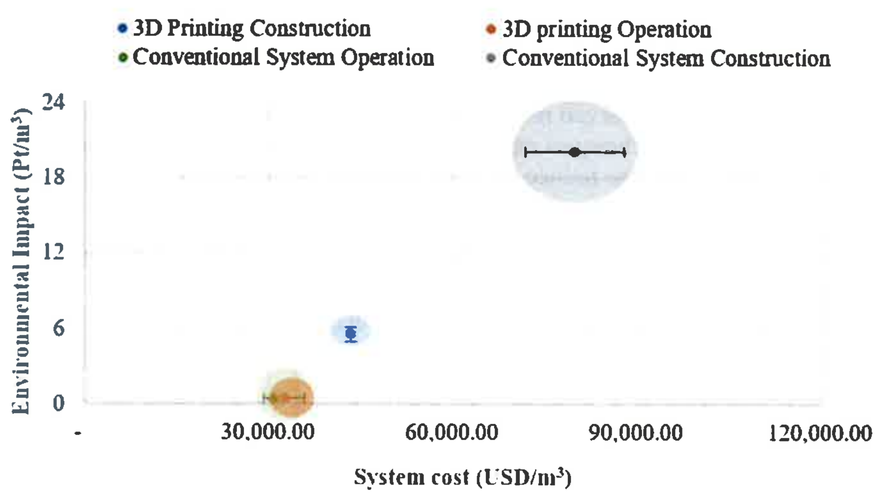

Figure 8. Uncertainty analysis of with +10% variation of 3D printing and conventional construction scenarios.

6. Study Limitations

Based on the conducted structural, environmental, and economic assessments, 3D printing is a viable alternative to conventional construction techniques. However, the findings of this comparative study were limited due to the unavailability of some important data, such as, (1) characteristics of the mortar used in 3D printing process, (2) varying ratios of conventional concrete ingredients, (3) limited number of investigated structural elements, (4) exclusion of sub-structure system and end of life phase, and (5) the common processes and components among the examined alternatives were not included, thus only relative environmental impacts were quantified, (6) inadequacy in 3D printing speicifc processing and (7) data inventory was calculated from diverse sources as a result of lack of data.

7. Conclusions

The evaluation of digital fabrication technologies, particularly 3D printing, has been adopted to enhance environmental performance and economics. This study compared (1) additive manufacturing by means of extrusion method and (2) conventional construction using cast in-situ concrete. The comparative analysis was performed on a single-storey house in the UAE from environmental and economic perspectives. The analysis utilized LCA using midpoint impact methodology ReCiPe 2016 to measure the relative environmental burdens. The LCCA analytical framework was conducted to determine the financial feasibility of the examined scenarios. The results of the LCA and LCCA analyses were combined using a ratio method to determine the system with the higher eco-efficiency. LCA analysis revealed better environmental performance of the 3D printing method due to the absence of several components, such as formworks, steel reinforcement and the lower use of materials, compared to conventional construction alternatives. From an economic perspective, the LCCA indicated that 3D printing is 78% more profitable than its conventional counterpart. The eco-efficiency analysis revealed that 3D printing was the optimum choice. The sensitivity analysis revealed that decreasing cement ratios in 3D printing mortars can significantly decrease the environmental impacts. In this study the 3D printing construction technology showed a better overall eco-efficiency. However, it is acknowledged that the number found in this study may differ for different comparative analysis conditions.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

3DCP	3-D Concrete Printing
ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building information modelling
CAD	Computer aided design
GWP	Global warming potential
EI	Eco-efficiency index
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
ISO	International organization for standardization
LCA	Life cycle assessment
LCC	Life cycle costing analysis
LCI	Life cycle inventory
LCIA	Life cycle impact analysis
PV	Present value
STL	STsereo Lithography
UAE	United Arab Emirates

Item A.

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Item A.

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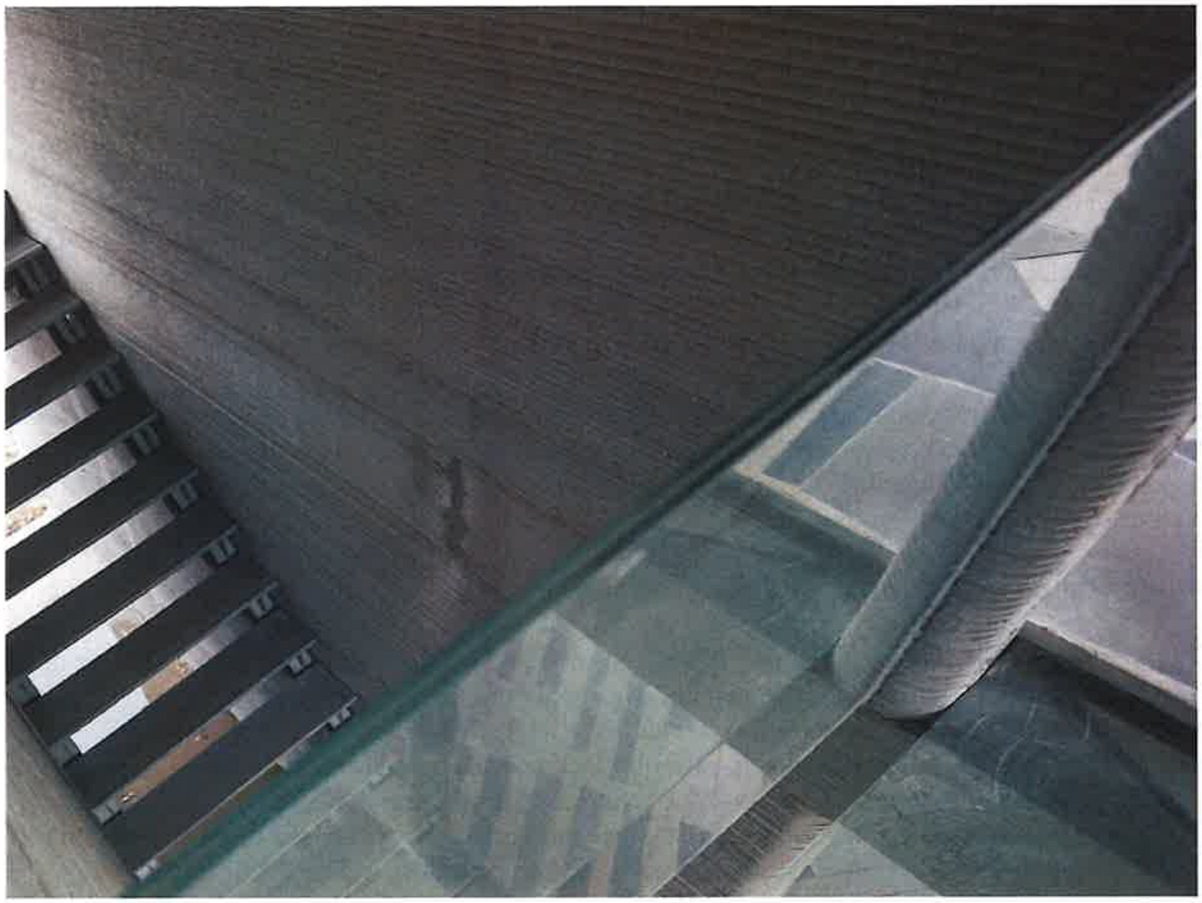
Build Trust in 3D Manufactured Buildings with UL 3401

How can code authorities gain trust in 3D printed structures to ensure they are safe, code compliant, durable, and can withstand the elements for their anticipated lifetime?



September 11, 2020

Authored by: Howard D. Hopper, FPE, Global Regulatory Services Manager

3D printing of physical objects is no longer a futuristic concept. This technique is being used extensively in homes, businesses and industrial applications. 3D printing is also being used to construct building elements and structures in locations around the world. If you have not seen how buildings can be constructed using 3D printing, simply search the internet for 3D printed building videos.

To fully embrace this new technology, stakeholders – including code authorities – need confidence that 3D printed structures are safe, code compliant, durable and can withstand the elements for their anticipated lifetime. In addition, variations in 3D printing materials and fabrication processes that can significantly impact a structure's physical characteristics must be addressed.

UL takes the lead in addressing challenges

UL has been researching safety considerations of 3D printing for more than five years. We determined that, unlike traditional manufacturing techniques, the 3D printing process introduces variability that significantly impacts properties and performance based on how products are printed. This research, which initially focused on plastic materials, led to the development of the UL Blue Card program in 2016.

In 2017, we began examining safety, durability and code compliance factors associated with 3D printed building construction. This research formed the basis for a 3D printed building construction evaluation methodology documented in UL 3401, Outline of Investigation for 3D Printed Building Construction. This methodology determines that a fabricator's 3D printing equipment, additive manufacturing material (AMM) and fabrication process will consistently produce building elements with properties that don't vary from the samples initially tested.

During the development of UL 3401, UL worked with building authorities to obtain their input on the scope of the evaluation program. Additionally, the program was discussed at two International Code Council (ICC) Major Jurisdiction Committee meetings to make sure building authority concerns were addressed.

Code compliance and acceptance challenges

Builders need to demonstrate that the 3D printed structures comply with applicable building or residential codes to gain building code authority approval for 3D printed construction in jurisdictions. Code compliance presents a challenge for both a builder and code authority because building and residential codes currently lack prescriptive requirements for 3D printed construction. Even code requirements for concrete construction are not directly applicable for cementitious-based 3D printed construction, since mortar and cement-based fabrication, printed in a layer-upon-layer fashion without forming members, are not specifically covered by the concrete standards referenced in the model codes.

Since there are no prescriptive code requirements for 3D printed construction, code authorities must consider each project under the alternate materials and methods provisions in the code for their evaluation and approval. This approach allows them to approve 3D printed building constructions, provided they are shown to comply with the intent of the code provisions and provide the code prescribed quality, strength, effectiveness, fire resistance, durability and level of safety. Using testing and evaluation data from standards such as UL 3401 is one recognized method whereby a code authority can determine equivalent code compliance for a 3D printed building.

UL 3401 evaluation fills in the gaps

UL 3401 covers the evaluation of building structures and assemblies such as panels, walls, partitions, floor-ceilings, roofs, columns and beams fabricated using an additive manufacturing or 3D printing process. The UL 3401 evaluation produces the technical information report needed to determine if a 3D printed building element complies with a given building code. The evaluation will also document compliance with performance (test) standards referenced in the code.

A UL 3401 evaluation determines that the key production elements adequately and consistently produce structures with properties equivalent to the 3D printed samples initially tested. These elements include:

- 3D printing equipment
- Fabrication process
- Additive manufacturing materials (AMM)
- Quality control procedures
- Production records

The evaluation covers properties such as:

- Mechanical properties
- Fire performance
- Vapor, air and water barriers
- Thermal insulation
- Indoor air quality
- Durability, integrity, and performance before and after environmental exposure conditions

The 3D printing production process is documented in a Fabrication Process Description report and referenced in the Report of Findings.

Testing considerations

Testing of 3D printed samples is required to determine compliance with referenced standards in building code, such as UL 723 (surface burning characteristics, UL 263 (fire resistance), ASTM E331 (water barrier), ASTM C1363 (thermal performance) and other standards.

In addition to testing required by the building code, UL 3401 includes requirements for material property and performance testing, both before and after environmental conditioning, to provide technical data on the durability of the 3D printed construction. Environmental conditioning includes UV exposure, water immersion and freeze-thaw cycling.

Because test performance can vary depending on several production factors, test samples are printed using the documented 3D printing fabrication process and associated 3D printing material (AMM).

Report of Findings

The UL 3401 evaluation produces a Report of Findings intended for use by designers and code authorities. This report describes the building element construction covered by the report, and identifies the fabrication process, 3D printing equipment and AMM used to produce the printed structure. It also documents any ratings, material properties, and material performance characteristics established by tests. The Report of Findings is provided to the sponsor of the evaluation, who can include it with required plan review construction documents necessary for the permitting process.

Code authority recognition

Thanks to public testimony provided by several building officials at ICC code development hearings, the 2021 edition of the International Residential Code (IRC) includes an adoptable appendix on 3D printed building construction. It requires buildings and structures fabricated in whole or in part using 3D printed construction techniques to be designed, constructed and inspected in accordance with UL 3401. Having these requirements documented in an nationally recognized code provides builders and code authorities with a sound technical basis for designing, fabricating and approving 3D printed construction.

For more information on the evaluation of 3D printed building construction, please contact Howard Hopper at Howard.D.Hopper@ul.com or Bob James at Robert.J.James@ul.com.

Item A.

Research and Feasibility Study on 3D Printed Homes in Rural Alaska

July 2021

Image Credit: ICON

Image Credit: Constructions 3D

Image Credit: Apis Cor

Image Credit: Apis Cor

Supported by:

Alaska Housing Finance Corporation

Denali Commission Alaska

Prepared by:

Xtreme Habitats Institute

Introduction

Alaska Housing Finance Corporation (AHFC) is pleased to present the Research and Feasibility Study on 3D Printed Homes in Rural Alaska.

Among AHFC's values is Leadership. In that regard, we endeavor to "Be a trusted industry expert and resource." This report is designed to advance a conversation about how exciting new technology may be applied to home construction that's relevant to the unique challenges our state faces – while also acknowledging the limitations of that technology.

As demonstrated in the 2018 Alaska Housing Assessment, rural Alaska housing is overcrowded and inefficient with residents spending a high proportion of their income on housing related costs. The rate of new construction is slow and at current production levels does not meet demand.

This study evaluates the use of 3D printing, known as additive manufacturing, as a potential approach to build high-quality, rapidly deployable, and low-cost housing in rural Alaska. The study offers insightful data on the benefits and challenges to build even in Alaska's permafrost regions. Furthermore, it examines the potential to reduce the cost of materials and the average time to build a home versus the conventional wood framework method. It also outlines the next steps to construct a 3D printed home prototype, which will further define the feasibility of 3D printed homes in rural Alaska.

I would like to thank the authors from Xtreme Habitats Institute and the Pennsylvania State University Department of Architectural Engineering and Civil Engineering for their research and authorship as well as their in-kind contributions. I would also like to thank the Denali Commission for their generous financial support and the University of Alaska Anchorage Business Enterprise Institute for their in-kind contribution of time collaborating on this study.

AHFC's mission is to provide Alaskans access to safe, quality and affordable housing. We hope this study proves a useful resource for others working with us overcoming Alaska's housing challenges and improving the quality of life for Alaskans across the state.

I encourage you to read the following study and learn about the feasibility of 3D printed homes in Alaska. With any comments or questions, please contact Jimmy Ord in our Research & Rural Development department at jord@ahfc.us or 330-8446.

Sincerely,

Bryan Butcher
CEO/Executive Director

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Purpose

The purpose of this Research and Feasibility Study (hereinafter "Feasibility Study" or "Study") is to explore the viability of 3D Concrete Printing ("3DCP"), a revolutionary innovation in the construction industry that could help to dramatically reduce the cost of housing in rural Alaska, and rapidly increase the pace of construction. 3DCP is an interdisciplinary practice that incorporates construction science, materials science, architectural, structural, mechanical, and software engineering disciplines. It begins with a Computer Aided Design ("CAD") that defines the details of the object, similar to a blueprint, which is then translated as precise instructions to a robot and pump that extrudes concrete and prints, layer by layer, to form structural components without the need for formwork. 3DCP has the capacity to build houses, buildings and other structures faster, at higher accuracy, and with far less waste and much lower cost than with conventional construction methods. Conventional construction methods, for purposes of this Study, refers to traditional methods of constructing houses with wooden frames.

Background

Figure 1: Construction 3D Concrete Printing

There is an increasing need for high-quality, affordable housing in rural Alaska. According to a State-wide Housing Assessment by the Alaska Housing Finance Corporation ("AHFC") in 2018, a significant portion of existing housing in rural Alaska is characterized by overcrowding, energy inefficiencies, and / or incomplete plumbing and kitchens due to a lack of water system infrastructure. Additionally, a high percentage of Alaska Native Villages located in coastal areas or near riverbanks in rural Alaska need massive refurbishment and in some cases relocation altogether due to flooding, rising sea levels, erosion and other impacts of rapid climate change.

According to the US Department of Agriculture's 2017 Alaska Rural Home Ownership Resource Guide, the estimated capital cost for making only the most urgent improvements to the housing stock in rural Alaska would be about $2 billion US dollars; the cost to replace just the homes that lack energy efficiency would be more than $4 billion; and the cost to replace all homes in rural Alaska that are over-crowded, cost-burdened or energy inefficient would exceed $27 billion. These estimates are based on the average total cost of development, which according to the USDA averages about $600,000 per house. The USDA's target for making this cost more affordable is in the range of $300,000 per house. While the cost of solving the housing problem in rural Alaska would still be astronomical, the billions in required funding would be reduced by half. 3DCP has the potential to bring the costs of construction down to or below the range targeted by the USDA.

While the cost of constructing the house is only part of the total development cost, it is the largest single component, likely accounting for at least one-half to two-thirds of the total cost. These costs are significantly higher in Alaska than in the lower 48 US States, and higher in rural Alaska than population centers like Anchorage, Fairbanks and Juneau. The reasons have to do with the high cost of construction materials (lumber, for example), transportation of the materials and equipment to the construction site with limited access via roads, airports or waterways, availability of skilled labor, and the time it takes to build a house in a remote area using conventional construction methods in a short construction season.

Opportunities

The potential advantages of 3DCP over conventional construction methods are many. First, it has the potential to dramatically lower the cost of construction, with respect to the foundation, walls and roof of the house. This is because of lower cost of materials, less formwork, less labor (it only takes two to four people to set up and operate the 3D concrete printer), shorter supply chain, lower logistics costs (3DCP equipment can be easily transported from one site to the next), design flexibility (geometric freedom; e.g., the ability to print houses with walls that are curved or straight), faster construction time, and greater efficiency (minimal waste of materials). The time required to print the outer shell of a small-sized house (e.g., 1,200 square feet) – foundation, walls and roof - can be as little as 24 hours (possibly spread across several days depending on local weather and other conditions), versus one to four months for a wood frame house via conventional construction methods. Further, where multiple houses are required in the same area or village, the 3D printer could build one house after another during Alaska's limited construction season, with significant economies of scale.

In addition to savings, other potential advantages of 3DCP are environmental impact (minimal impact on critical natural resources such as trees from Alaska's forests), durability, with concrete housing structures expected to last at least 50-75 years, sustainability, with the ability to recycle the concrete structures at their end of life, a safer construction site, since the use of robots for printing the structure will reduce many of the hazards otherwise faced by construction crews during the construction process, and new business and employment opportunities in Alaska's construction industry, for the operation and maintenance of 3DCP equipment, supply of materials for 3DCP construction, and additional support activities during construction and for maintenance of the new housing structures.

Challenges

While 3DCP technology has evolved rapidly over the past 20 years, riding the wave of advancements in software, robotics and materials science, it is still in the early stages of commercial rollout, and still innovating with printing equipment and techniques, blends of concrete, and requisite trade skills. Further, as a new construction method, 3DCP is not included in current building codes. However, 3DCP houses on an individual basis have received building permits in a number of countries around the world, including in several local jurisdictions in the United States, based on engineering analysis demonstrating that the house meets or exceeds the requirements on which the local building codes are based.

Various construction code organizations are considering the incorporation of 3DCP into existing housing codes.

Additionally, 3DCP in rural Alaska has its own unique set of challenges. These include: logistics of transporting 3DCP equipment and materials in rural areas; impact of extreme climate conditions during the construction process; demonstrating the ability of 3DCP houses to withstand permafrost heaves, seismic activity, snow loads, wind and other environmental factors; demonstrating that 3DCP is a cost-effective alternative or complement to conventional construction methods; and overcoming local scrutiny and skepticism. 3DCP as a new technology will need to pass heavy scrutiny of the local community with respect to its acceptability as a viable alternative to conventional construction methods, with such considerations as housing design, functionality, comfort, cultural acceptability, durability and sustainability. Rural Alaska is so vast and geographically diverse, the outcome of these considerations is likely to differ from one community to another throughout the different regions of the State.

Scope of Study

The scope of work for this Study comprised the following six Tasks:

Task 1: Applicability of 3D Printing Technology to Rural Alaska:

This Task reviews the literature concerning the applicability of 3DCP to rural Alaska, including operational aspects: 3D printers, software and concrete mixes; architecture and engineering for 3DCP housing structures in rural Alaska, including the Alaskan Arctic, construction methods to mitigate permafrost impacts, thermal insulation considerations, and optimal methods for 3DCP structures in Alaska.

Task 2: Research and Analysis for 3D Printing Companies:

This Task examines the key characteristics of various 3D concrete printers developed by firms around the world, with the objective of identifying those printers best suited for printing houses, buildings and other structures in rural Alaska.

Task 3: Engineering Analysis of Concrete 3D Printed Structure:

This task was sub-contracted to the Additive Construction Laboratory ("AddConLab") of Pennsylvania State University ("PSU"), a collaborative effort between PSU's College of Engineering and its Department of Architecture, which specializes in additive manufacturing at construction scale. The AddConLab was tasked to conduct an engineering analysis of conceptual 3D printed small housing structures designed for rural Alaska, particularly the Alaskan Arctic.

Task 4: Materials Analysis Re: Selection and Use of Geologic Material in Different Alaskan Regions for 3D Construction:

PSU's AddConLab was also tasked to test sample geologic materials (e.g., sand, gravel, rock, etc.) from different Alaskan regions for use as aggregate in concrete mix form 3D printing.

Task 5: Cost / Benefit Comparison Analysis of 3D Printed Housing vs. Conventional Construction:

This Task compares the costs and benefits of conventional construction methods with those of 3D printing, to build a single model 1200 square foot model house, as well as economies of scale and time savings for construction of multiple units. The data for this comparison is R.S. Means 2021 cost estimates, along with construction cost surveys for rural and remote locations throughout the State conducted by the Alaska Department of Labor.

Task 6: Program Plan for Phase 2:

This Task recommends a plan for a Phase 2 Study: to build a complete model house using 3DCP, in order to stress-test all of the conceptual analyses and conclusions reached in this Research and Feasibility Study.

Methodology

The methodology used in this Study included an analysis of peer-reviewed scientific and engineering published research on the subject of 3DCP and a global review of firms manufacturing and selling 3DCP printers and their characteristics. It also included review of materials by Alaska's experts in rural residential housing construction, such as Cold Climate Housing Research Center, Alaska Housing Finance Corporation, and the seminal works: "Alaska Residential Building Manual" by University of Alaska, Fairbanks (2007), and "Building in the North" by Eb Rice (2008). These works take into account not only the research conducted over past decades, but also the experience and lessons learned by Native populations of Alaska and their adaptations to the challenges of living and working in the Arctic well before contact with the first white explorers and the importation of their southern housing designs and associated inefficiencies. The value of this experience with respect to Arctic architecture, e.g., shape and design of the house, building on permafrost, heat conservation, insulation, vapor proofing, ventilation, Arctic entry, and many other considerations, is directly relevant to 3DCP, in order to avoid making past mistakes going forward.

The methodology for the Study also included research and analyses by PSU's AddConLab, as a subcontractor to XHI, of the architectural, engineering and materials aspects of 3D concrete printing of small housing structures on permafrost in the Alaskan Arctic. PSU designed four different 3DCP habitat models based on residential construction requirements for building on permafrost in rural Alaska. The designs included both a pile system for raised foundations and a slab on grade without excavation (solidly raised above ground). PSU further conducted a structural analysis of the designs based on application of loading factors derived from historical data regarding dead weight, snow loads, wind and seismic loads. Other elements examined by PSU with respect to the habitats models included: thermal insulation and thermal bridges, vapor walls to mitigate condensation, ventilation, sanitation, outer coatings, etc. The resulting analysis from PSU's work under this contract, hereinafter referred to as "PSU Design and Engineering Analysis" is attached as Appendix A to this Study.

Further, the methodology included a cost benefit analysis of 3DCP as compared to conventional construction for rural Alaska, and a project management plan to implement a 3DCP prototype model house for "field and stress testing" the results of this Proof-of-Concept Study.

Key Findings

The Key Findings in this Feasibility Study are based on the research and analysis conducted by XHI and PSU. Support for these findings is set forth in the Task sections of this Study and the PSU Design and Engineering Analysis attached as Appendix A.

- 3DCP is a rapidly maturing technology that is likely to have a significant impact on conventional construction methods for houses, buildings and other structures, including the ability to construct high-quality, affordable houses and communities, at a much faster pace, throughout rural Alaska including the Alaskan Arctic (See Tasks 1 and 2 of Feasibility Study).

- With 3DCP, it does not make any difference to design and/or print straight or curved walls. Further, the advantage of 3D printing is that structures can be mass produced, with each of the mass-produced structures customized, resulting in mass customization. In other words, 3DCP can produce custom made buildings without added cost (See Task 1 and PSU Design and Engineering Analysis).

- PSU's structural analysis of the conceptual habitat models it designed considered applicable load combinations for dead weight, snow, wind and seismic loads. On the basis of its analysis, PSU concluded that the schematic designs of the habitats it designed can work safely under all applicable loading conditions (See PSU Design and Engineering Analysis).

- PSU's analysis also recognizes that since concrete itself generates less than R-1 per inch depending on density, other insulating materials will be required to meet the stringent thermal insulation requirements for housing structures in the Alaskan Arctic. The 3DCP structure can accommodate a variety of insulation approaches, by printing a single or double shell and the placement of the insulation layer inside, outside, in between the shells, or a combination of both (See PSU Design and Engineering Analysis).

- Gantry-style and robotic arm 3D printers each have strengths and weaknesses with respect to their adaptability to printing houses in rural Alaska. Key considerations in selecting a printer should include the characteristics and accessibility of the terrain where the construction is to take place, size and scale of the housing structures to be printed, and then, with respect to different printer options, such things as maximum build size, transportability, mobility, open source or proprietary construction material and cost (See Task 2 of Feasibility Study and PSU Design and Engineering Analysis).

- Samples from three Alaska sites (Anchorage, Juneau and Fairbanks) were tested as aggregate for the concrete mixture to be used for 3DCP in Alaska. All aggregates tested have proven to be a viable option for 3D printing operations in Alaska. The results revealed that all aggregates resulted in mortars reaching structural strength in 28 days with each sample demonstrating more than 6,000psi in compressive strength (See Task 4 of Feasibility Study and Appendix B).

- Based on data from the 2021 RS Means Residential Construction database and 3DCP equipment, materials and logistics cost data from various sources, building the exterior of a house (i.e., foundation, walls and roof) in Fairbanks, Alaska with 3DCP, would cost an average of $12.97 per square foot, as compared to $51.38 per square foot using conventional construction methods. This cost difference would be substantially greater in remote rural areas of the State, such as Bethel, Nome and Barrow, where the cost of conventional construction is higher than Fairbanks by at least 71%, 85% and 128%, respectively (See Task 5 of Feasibility Study).

- Several firms that manufacture 3DCP machines have demonstrated the ability to build 3DCP house exteriors from start to finish within a 24 hour period, in some cases spread over several days due to local weather and other conditions. During the construction season in Alaska, depending on the location, 3DCP can build up to ten times more houses than conventional construction. 3DCP economic efficiency increases with more houses built on the same site and is suited to build communities or villages. This could be of particular relevance with respect to Alaska Native villages in need of reconstruction or relocation due to severe impacts of climate change (See Tasks 2 and 5 of Feasibility Study).

Recommendations

The results of this Feasibility Study indicate the high likelihood that 3DCP could be a viable, cost-effective alternative to conventional wood frame construction in rural Alaska. However, in order to demonstrate and validate the results of this Study in the field, as well as refine and revise architecture and engineering assumptions as needed in the course of actual construction, it is recommended that the Study's proposed Program Plan for Phase 2, which includes using a 3D concrete printer to build, stress-test and observe over multiple seasons a complete model house at a selected site in rural Alaska. Phase 2 would also provide the opportunity for extensive involvement and input from local communities, tribes, government agencies and citizens in every important aspect of this critical field-test from start to finish.

TASK 1: ASSESSMENT OF ADDITIVE MANUFACTURING AND RELEVANCE TO LOW-COST HOUSING IN ALASKA

Introduction

This Study explores the viability of 3D Concrete Printing ("3DCP") as a potential means of reducing the cost of housing in rural Alaska, and to rapidly increase the pace of construction. 3DCP is an interdisciplinary practice that incorporates construction science, materials science, architectural, structural, mechanical, and software engineering disciplines. Construction of 3D printed homes begins through a Computer Aided Design ("CAD") or digital file and Business Information Modelling ("BIM") that defines the details of the object, similar to a blueprint. Rapid manufacturing, rapid prototyping, additive manufacturing, digital manufacturing and 3D construction, all refer to the family of processes. These processes all produce components by adding, or building up, material to form an object. Once in production mode, the 3D printer utilizes materials such as concrete and a range of additives to construct structural components. For constructing houses, buildings or other structures, a specialized cement and additive mixture is thicker than concrete so there is typically no need for formwork. When this technology is applied to construction there is capacity to build far more complex structures faster, at higher accuracy, and with far less waste and much lower cost than with conventional construction methods. Conventional construction, for purposes of this Study, refers to traditional methods of construction typically built with a foundation of poured concrete or other framing, of walls and roof by a system of repetitive wooden frames.

Alaska's conditions are assumed in this Study including Arctic cold or long cold periods, permafrost in some areas, geographic remoteness, Alaska's State-wide transportation system characteristics and constraints, current conventional construction methods, resource constraints in some areas, and a constrained labor supply of skilled trade workers (workers licensed as carpenters, plumbers, masons, electricians, and HVAC technicians).

Alaska's conditions including distance from the lower 48 States clarify the following practical goals of any construction and especially 3DCP:

- Use local construction materials and labor to reduce cost of importing expensive fabricated products, materials, or skilled trade labor;

- Reduce transportation costs;

- Use construction methods and materials compatible with Alaska's climate and soils; and

- Incorporate extremely important house and community preferences of Alaska's diverse Native people. A detailed community preference survey analysis is beyond the scope of this Study, but must be done prior to construction to guide plans for homes and communities. In this Study, only general historical Native Alaskan preferences for houses or communities are cited, mostly derived from historical time-period photos or plans.

3D Concrete Printing Technology for Rural Alaska

Additive Manufacturing or 3D printing began as rapid prototyping (rapid making models of items such as a machine part or a wall using a robot) developed in the late 1980s by Kodama of Japan. Since then, use of 3D printing with concrete as the construction material for houses, buildings or other structures has evolved globally.

Use of 3DCP to build homes stems from several factors. Current conventional home building methods have changed little in the past 100 years. And, commonly used building codes are based on construction methods over 100 years old which are a major obstacle to implementing 3DCP but are currently being addressed.

Figure 2: Conventional Construction House

Home Building Method 1928 Like Today
(Industry Film Archive 2014)

Applying 3DCP can overcome typical construction challenges (Warszawski and Navon 1998). Advantages of 3DCP construction include savings on construction materials, transportation and labor, faster construction, less wasted materials, and the ability to construct more complex structures with increased accuracy, to name a few. And, of special benefit to architects and designers is freedom of design and non-necessity to conform to regular building shapes (see following figure). Buildings constructed by 3DCP can be square, round and any pattern in between. “Therefore, 3D printing could be the best option for construction in a remote area where the environment is aggressive for humans.” (Panda, B., et.al. 2018, p. 667).

Figure 3: 3DCP House Designs

Ten 3DCP Square Houses
Built in 24 hours; 2014

3DCP Round House Built in
24 hours; Winter 2017

Operational Aspects of Concrete 3d Printing: Viscosity, Mixes, Robots and Forms

While first conceived in the 1990s, use of 3DCP to build houses and other structures has started to spread during the past five years in an increasing number of countries, including the United States. In addition to the potential advantages of 3DCP mentioned previously, it has been fueled in certain countries by labor shortages, the need for rapidly built structures and the higher cost of conventional construction, as with the affordable housing initiative by ICON in Austin, Texas.

3DCP construction is guided by precise CAD and BIM software that drive a robot controller. Robot controllers vary in configuration of a robot arm, a robot controlled by a gantry, or a robot controlled by cables attached to four posts. All types can be transported to a construction site, and some can be moved around a construction site.

Figure 4: 3D Concrete Printer Types

Robot Arm 3DCP

Gantry 3DCP

Cable 3DCP

The robot can have one or more “printing” nozzles that force the flow of concrete. The concrete can be made of various ingredients to improve use for 3D printing and structural strength. Typically, Portland Cement is mixed with small particle aggregate such as sand grains smaller than 9mm, preferably 5mm to reduce wear on the nozzle. Other ingredients (binders) are being experimented with such as geopolymers, fly ash, fibers and others (Panda, B., et.al. 2018, p. 669). The cost of the 3D concrete mix to print the complete outer shell of a house (foundation, walls and roof) is significantly less than the cost of materials for conventional construction of the same structure. In Fairbanks, Alaska, for example, Portland Cement cost $17.28 per 94-pound bag (Lowes Fairbanks AK June 2021) that can be mixed with local sand-size material to make one cubic yard of concrete. The total cost of the Portland Cement for a 1200 square foot house would, conservatively, be $20,308. Prices may vary by geographic location throughout Alaska.

To print correctly, the concrete must have a viscosity allowing it to flow from the nozzle and keep its form as applied and not flow off the structure. Viscosity is controlled by the concrete ingredients and the amount of water added to the concrete. "Recently, five key benchmarking properties such as extrudability, flowability, buildability, open time and layer adhesiveness have been introduced, in an attempt to benchmark the concrete materials for extrusion-based printing process." (Panda, B., et.al. 2018, p. 668). In Alaska's case, water must be available near the construction site either, trucked in or from a local water source (e.g., well, pond or river).

According to Panda et.al., challenges to 3DCP construction include materials, structural integrity, post-processing and reinforcement. Materials must have the correct strength and viscosity. Structural integrity must be ensured between printed layers (joints) and connected structures that may have shrunk during curing or contain voids in the concrete. "Poor surface finish (due to volumetric error) has been a limitation in concrete printing. Improper control and excess deposition of materials can cause poor surface quality in the part, which is not desired." (Panda, B., et.al. 2018, p. 668). Reinforcement can be done by inserting bars into the concrete layers or by design of the concrete layer such as an internal printed pattern. These challenges, with emphasis on structural integrity (e.g., compression, tensile and torsional strength with respect to dead weight, permafrost heaves, snow loads, wind and seismic activity) are addressed in the Structural and Materials Analysis Report by PSU's AddConLab, attached to this Study as an Appendix, and will be extensively field-tested in Phase 2.

As indicated in PSU's Report, these challenges can be mitigated by careful printing processes. Further in this regard, Panda et.al. (2018) and Murcia et.al. (2020) observed from pressure tests that 3D printed concrete strength is comparable or superior to cast concrete. Like cast concrete, 3D printed concrete strength increases with number of days to cure.

Figure 5: 3D Printed Concrete Samples Average Strength by Days

(Apis Cor 2019 p. 6)

The operation of 3DCP to build housing is normally done by private construction contractors. Early examples of 3DCP houses have predominantly been built in countries with more flexible or no building codes (e.g., ICON 3DCP houses in Mexico), as opposed to countries like the United States, where local codes are generally more restrictive. However, in a few cases government is a collaborator to modify building codes to allow 3DCP houses. There are a few cases of firms and U.S. local governments that clarified with engineering analysis how 3D printed construction is like certain code requirements and thus permitted to build by 3DCP. Following are several examples.

Educating and negotiating with local governments to accept 3DCP structures is possible, through the modification of local codes or issues of waivers for compliance. The 3D printing company ICON states on its website that its homes are built to the International Building Code ("IBC") structural code standard. ICON was the first company in the United States to be awarded a building permit to 3D print a house in Austin Texas. More recently, another 3D printing company, Apis Cor, in collaboration with the Housing Trust Fund of Santa Barbara ("HTFSB") received a building permit from the City of Colida, California, for a 3D concrete printed one-story home (based on a third-party engineering Study provided by Apis-Cor). Apis Cor is also working with HTFSB to secure a building permit from Santa Barbara County, but will need to provide further engineering analysis. The printer company SQ4D has been awarded a building permit to 3D print a house in Riverhead, New York, which has very stringent building code requirements. Similarly, Twente Additive Manufacturing ("TAM") was awarded a building permit for a house in Nelson, British Colombia, after working closely with the Regional District of Kootenay, B.C., to use engineering calculations with respect to the material properties of the 3D printing mortar – strengths, freeze-thaw performance, thermal conductivity, and coefficient of thermal expansion, and overall construction method, as a substitute for known construction conditions.

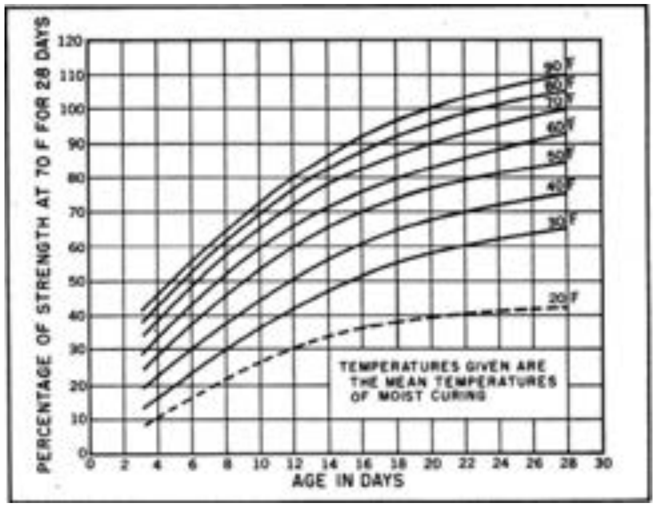
In the case of Alaska construction contractors, meeting requirements of Alaska Cold Construction contractor licensing could be implementors of concrete 3DCP structures. However, existing Alaska local government building codes may be a challenge to use 3DCP depending on the location.

Methods to Mitigate Permafrost Impacts

One of the first definitive publications on structural design to mitigate impacts on permafrost was published in 1950 by U.S. Navy Commander Palmer Roberts, Officer in Charge of Construction, Naval Petroleum Reserve #4 in Alaska (Roberts 1950). While an older publication, his experience and analysis with respect to military construction in the Alaska permafrost in the late 1940's is particularly insightful. He collected detailed recordings on the use of concrete in his Alaska project. He stated, "Special problems arise when concrete is poured against a frozen face or in permafrost which will thaw upon contact with the concrete. Under such conditions water is produced which may initially cause settlement and later freeze with the possibility of heaving and resultant damage to the structure. In the case of vertical walls being required against a frozen face precast sections may prove more satisfactory. Slab construction in permafrost requires suitable insulation between the concrete and the permafrost" (Roberts 1950, p.177).

A related issue is the concrete curing time according to ambient temperature. While concrete can be satisfactorily cured at any low temperature above freezing, the optimal temperature is around 70 degrees Fahrenheit for fastest curing. As shown in the following figure, the lower the temperature, the more days to cure.

Figure 6: Concrete Cure Time in Days by Temperature



(Roberts 1950, p. 176)

American Concrete Institute (2016) analysis of concrete strength curing by temperature had similar results to Roberts 1950. While 70 degrees Fahrenheit affords the fastest curing time to maximum concrete strength at 28 days, curing concrete can occur at any temperature above 32 degrees Fahrenheit as described by the American Concrete Institute following Figure. Another factor for further consideration is the impact of cold temperatures combined with high relative humidity on the setting and curing process. This is proposed to be addressed in Phase 2 of this Study.

Figure 7: Concrete Curing Time by Temperature

Percentage of standard-cured 28-day strength	At 50°F (10°C), days			At 70°F (21°C), days		
	Type of cement			Type of cement		
	I	II	III	I	II	III
50	6	9	3	4	6	3
65	11	14	5	8	10	4
85	21	28	16	16	18	12
95	29	35	26	23	24	20

(ACI 2016, p. 13)

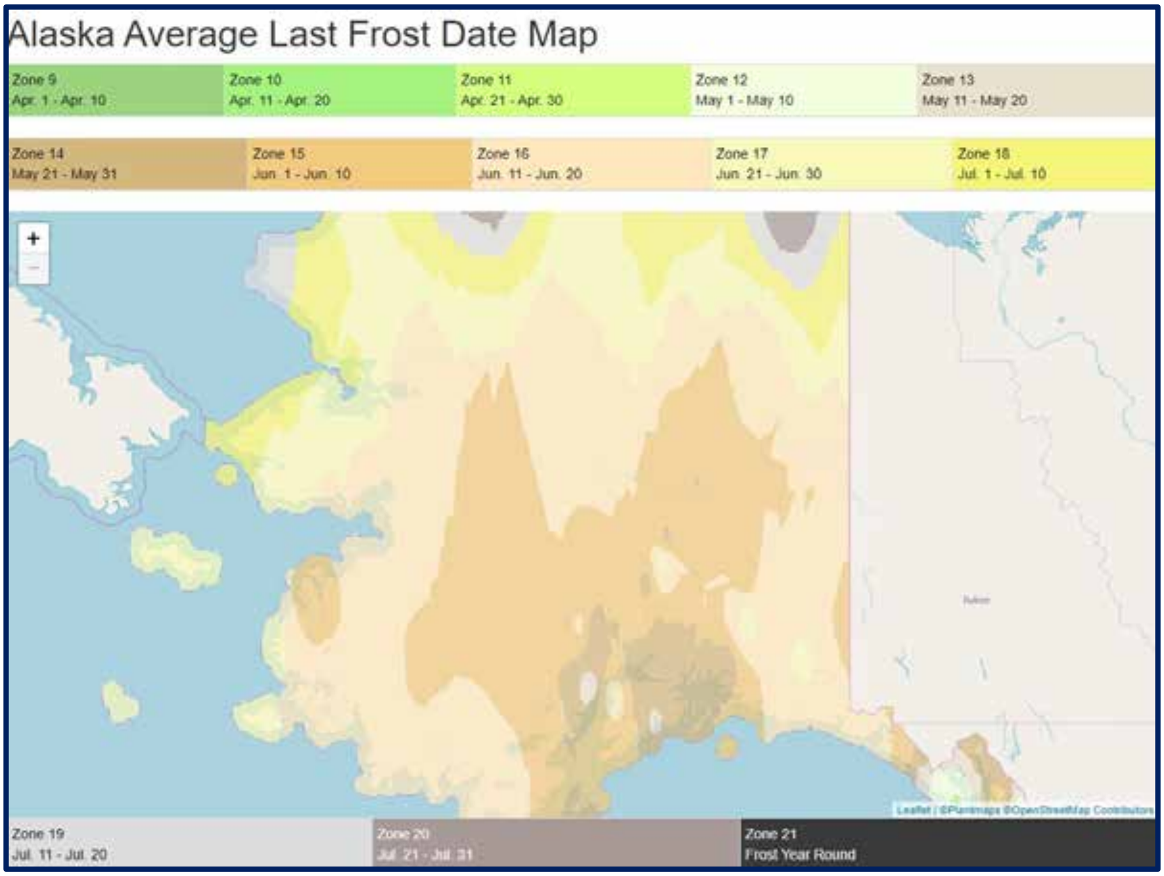
The ACI further states in its 2016 Guide to Cold Weather Concreting that “concrete placed during cold weather, protected against freezing, and properly cured for a sufficient length of time, has the potential to develop higher ultimate strength (Klieger 1958) and greater durability than concrete placed at higher temperatures. It is susceptible to less thermal cracking than similar concrete placed at higher temperatures" (ACI 2016).

Construction methods to minimize heat transfer from structures to permafrost have been developed by several researchers and engineers. Roberts (1950) recommends use of preformed concrete that has insulation as a method to prevent permafrost melting. In the past twenty years a few construction methods are used to prevent permafrost melt. The methods include the structure on pilings with space (1+ meters) between the ground and structure bottom floor to allow the flow of cold air underneath (McFadden 2001). Another more expensive method, requiring maintenance, is to incorporate a cooling system with the structure foundation or under it. Generally, newer Arctic and Antarctica structures use piling supports with a space between the ground and structure bottom floor as shown in the following photo of the U.S. National Science Foundation research center in Antarctica.

Figure 8: U.S. NSF Research Center in Antarctica On Pilings

Like conventional construction with concrete foundations, 3DCP of structures is constrained by freezing weather. Alaska's freeze periods vary from one area to another due to its vast geographic size. Concrete should be poured after last frost dates to prevent ice in the concrete that will melt causing concrete damage.

Figure 9: Alaska Last Frost Day by Region



Most of Alaska has potential sites for 3DCP according to the last frost days shown in the above Figure and the fact of needing three days to build a 3DCP a structure. Starting 3DCP after last frost dates provides adequate time to complete construction of houses and other structures. While 3DCP can be finished in the first week, interior build out can continue into the winter.

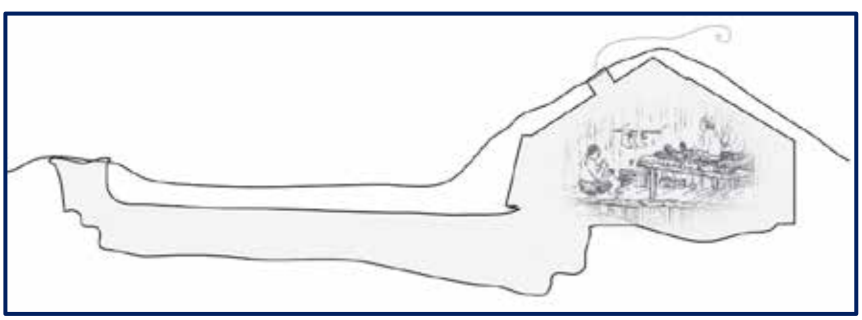
Structural Designs for Extreme Habitats: Cultural, International and Innovative Engineering

For 3DCP housing for Alaska's environment there are several sources of structural designs: cultural (local design) vernacular architecture, international concepts and designs for the most extreme environmental conditions. These concepts are further narrowed according to Alaska's economy and demographic situation of an expensive or limited supply of construction resources.

Cultural / Local Designs: Alaska's traditional housing design used local materials, local labor and used design to minimize inside cold (Seifert 2008). While the snow house is well known there was also a house design for warmer weather (Hirst 2020). The design used the "Roman Arch" developed by Roman architects of 3rd Century B.C. that improves structure strength with layers of material (bricks, ice blocks, etc.) that join at the top of the structure. This design results in a round floor. The Native Alaskan snow house used the same "Roman Arch" design with compressed layers of blocks to improve structural strength. To prevent intrusion of cold air, a tunnel entrance was used to minimize cold wind, and inside the floor was elevated to a sleeping area. For fire smoke there was a roof vent as shown in the following Figures.

Figure 10: Native Alaskan House 1909

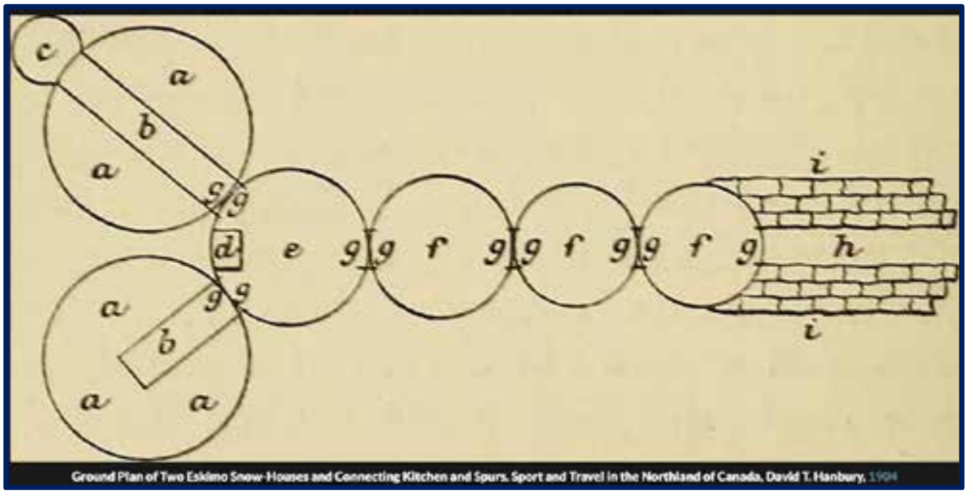
Figure 11: Traditional House Design Preventing Cold Air Intrusion



(Seifert 2008 p.2)

To further reduce exposure to the cold, North America Arctic Native People connected houses to functional areas such as kitchens and tunnels to the outside shown in following plan from 1904.

Figure 12: North America Arctic Native Extended Housing Plan



Different Houses (a) Attached to Functional Areas (e & f) for Communal

In recent years, the Cold Climate Housing Research Center ("CCHRC") has developed a number of manuals and guidelines for developers, homeowners, government, financial institutions and all stakeholders in developing design and construction practices that consider various critical aspects of constructing houses in the Arctic. For example, these manuals address ways to reduce construction time and cost, make houses more comfortable, more energy efficient, healthier to live in, more functional, etc. CCHRC has also worked closely with different Alaska Native communities to develop prototype plans for individual houses and sustainable communities (CCHRC Community Involvement 2021).

<u>International 3DCP Habitats</u>: Firms and local governments in other nations (Denmark, Italy, Netherlands, United Arab Emirate Dubai, Germany, China and Russia) have led the way in designing and implementing 3DCP of houses and communities. Design concepts from international sources include historic house architecture and community design, like traditional Native Alaskan housing and communities, that has evolved to innovative design concepts using 3DCP. However, there are challenges mostly from local building codes based on older construction methods, and construction firms and workers lack of knowledge of 3DCP.

> Little progress has been made towards appropriate standards for materials, including substitution of performance-based, more environmentally-friendly earth based and organic materials for high energy-consuming cement and burnt bricks. A major problem is that the regulations in force in many countries are still materials-based rather than performance-based. (UN 2016).

International building methods more often include high-density mixed land use community development, as opposed to widely spread-out development that is more characteristic of urban areas in the lower 48 United States. The higher density building method affords better access to various services, sustainable development, minimal ecological footprint of distributing wastes, climate change mitigation, local economic linkages, empowerment of citizens in policy making, improved master planning, and updated government codes (UN 2016). The international community design methods are similar to many Alaska Native villages, which tend to be concentrated in nature with housing in close proximity while the community itself is hundreds of miles from any other community. For survival, the core community is grouped together to build and maintain fundamental infrastructure.

International housing and community designs favor 3DCP as will be described in detail in Task 5 of this Study. In summary, the benefits of 3DCP dramatically increase when more houses and other use structures are built in close proximity to each other.

The following Figure shows international 3DCP housing and community construction.

Figure 13: International 3DCP Buildings & Communities

Russia House	Germany House	Italy House
		
Dubai Office Building 	Mexico 50 Home Community 	Netherlands Community 

<u>US Government 3DCP Innovative Engineering</u>: The U.S. and other national governments have spent billions of dollars to research, engineer, and test habitats and related technologies for space and extreme environments. The U.S. government Lunar south pole Base Camp effort addresses construction issues like Alaska's: expensive transport of construction materials, limited labor (astronauts), an extremely cold environment (minus 200 degrees Fahrenheit) and limited solar exposure. After 50 years of multibillion-dollar research and cost-benefit analysis for permanent, sustainable Lunar and Mars habitats, the conclusion is to use 3DCP structures using Lunar and Mars locally available dirt and cement as the building material (Lee et.al. 2018 and Mueller et.al. 2019). Furthermore, several U.S. government agencies conducted 3DCP research and development for various operations including extremely cold climates or in remote areas that the military may use.

Figure 14: US Government Agencies Research & Development 3DCP

MARINES 1st 3DCP Barracks 2018	ARMY Barracks
	
NASA Lunar Base	ENERGY Cable 3DCP
	

Images Courtesy of USMC, US Army, NASA and DoE.

<u>Structure Foundation Concepts for Permafrost</u>

There are several methods for building a structure foundation on permafrost: on-ground foundation slab, pilings or a floating foundation. Due to possible permafrost melting, each method must be adjustable to changes in ground elevation. A foundation method should use local resources and be easiest to install, maintain and adjust (McFadden 2001).

Due to its weight and linear size the on-ground foundation (a concrete slab) is difficult to adjust to changing ground elevation. Perimeter segmented hydraulic bladders under the foundation could be adjusted to correct for ground elevation changes. However, the foundation could still have linear cracks and the bladders may affect the permafrost.

Piling support for foundations are extensively used in cold climates, and also in areas susceptible to earthquakes and flooding. Commonly used in Alaska, pilings are installed in a hole or pounded into the ground. A jack mechanism between the top of the piling and the foundation is used to adjust the foundation to changes in ground elevation. The piling is wrapped in insulation to reduce effects on permafrost. The foundation elevated on pilings provides the flow of cold air beneath the foundation, preventing heat transfer from the foundation to the permafrost, thus avoiding impact to the permafrost state.

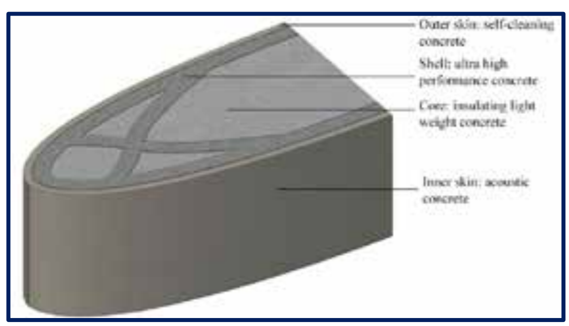
A floating foundation is related to the physics of ships with concrete hulls. The volume of displaced material floats the foundation. With equal distribution of weight, the floating foundation will naturally correct to stay level. However, this method assumes the permafrost is melted or in a semi-liquid state.

Pilings are the preferred method to support the concrete 3D printed structure. Pilings can be locally sourced, easy to install, can be adjusted, have the structural strength to support buildings and have a minimal impact on the permafrost. With the exception of locations where heavy equipment is needed to install the pilings, and such equipment is not available locally, pilings should not be a major cost for 3DCP houses. Alaska firms advertise $500 per installed piling for sale for heavy weight houses (Techno Metal Post 2021).

<u>Concrete 3d Printed Structure Insulation Methods</u>:

In addition to a building's internal insulation of an interior wall with insulation materials between it and the 3DCP outer wall, concrete 3D printed walls can increase insulation by the printed pattern providing air-pockets in the wall (Murcia et.al. 2020). Insulation material can also be incorporated into the concrete mix (e.g., cork, hemp, etc.) or inserted in the 3DCP wall air pockets as shown in the Figure below to increase thermal resistance R factor (Bos et.al. 2016, p.210). Foamed concrete can also be used as part of the 3D printing process for this purpose (Narayanan et. al. 2000).

Figure 15: 3D Printed Concrete Wall with Air Pockets Pattern & Added Insulation



Analysis of 3D extruded concrete compared to cast concrete reveals 3D extruded concrete has 18% lower thermal conductivity. Microscopic examination shows the extruded concrete has more microscopic air pockets than cast concrete attributing to 3D extruded concrete superior insulation (Falliano et al. 2019, p.284).

Ingredients for Concrete 3d Structural Construction in Alaska: by Physical Geology Type and Region.

Alaska has many, large-quantity sites that, with proper permitting, could be used for the extraction of local geologic materials for concrete 3D printing. For example, for the planned deep-water seaport expansion in Nome, Alaska, the U.S. Army Corps of Engineers estimates that 2,533,400 cubic yards of rock, gravel and sand material will be dredged (U.S. Army Corps of Engineers 2020). Many other locations throughout Alaska have gravel and sand in, and along the banks, of rivers and creeks, that can be dredged to filter out particles of less than 5mm in size for 3D concrete mixtures, with larger sized gravel and rock returned to the dredge source. There are also many permitted borrow pits. For example, there is a 200m diameter permitted gravel borrow pit near Nome. Note, however, that before these natural resources can be extracted for such use, there is an extensive permitting process that must be completed, in order to protect the environment and cultural concerns. Permitting processes can be expensive and time consuming.

Samples from three Alaska sites (Anchorage, Juneau and Fairbanks) were tested by Penn State University's AddConLabs as aggregate for the concrete mixture to be used for 3DCP in Alaska. The samples vary in geology. The Anchorage sample consists of mostly sedimentary geology. The Juneau and Fairbanks samples are mostly metamorphic or igneous geology. Results of the tests are included in Appendix B. The results indicate that the compression strength of the tested material exceeds the minimum requirements for construction of residential housing in Alaska's rural areas including the Arctic.

Extensive prior scientific research and analysis reveals concrete 3D printing to be a viable method to construct housing in remote areas of Alaska, and according to 2021 surveys of Alaska regional housing authorities, Cook Inlet Housing and North Pacific Rim Housing Authorities stated 3DCP houses could benefit their communities. The scientific research elaborates compared to current conventional construction, 3DCP of structures reduces time to construct, requires less skilled labor, reduces construction waste, provides greater structural strength, and can use local materials. All of these factors contribute to a reduced cost of housing construction and maintenance, and increased production capability. The details of costs and benefits of 3DCP are set forth in Task 5 of this Study.

Optimal Methods for Concrete 3d Printed Structures in Alaska

Based on research cited herein and input from various sources in Alaska and subject matter experts, concrete 3D printed structures can be built in Alaska. A concrete 3D printer system can be transported to Alaska sites by ship, truck, barge or aircraft depending on the location of the site. The majority of materials for pilings and concrete ingredients can be accessed locally. In addition to the 3D printer system, other equipment can be leased in, or transported to, Alaska. Depending on the selected site and type of 3D printer, additional equipment may include a sub-set of the following: portable dredge, portable rock crusher, electric generator, portable concrete mixer, small tractor backhoe with scoop, a forklift, an ATV with trailer, water truck and hand tools.

All equipment can be shipped prior to the construction season to a particular site or holding area. In late spring or early summer equipment can be assembled and materials acquired on the site. Assuming the ability to secure the requisite permitting, availability of materials, equipment, and construction crew, and weather permitting, concrete 3D printing of a housing structure can be completed within a few days.

Piling holes are dug and pilings insulated and inserted into holes. Mechanical jacks with small platforms will be attached to the top of pilings. The concrete 3D printer can consecutively print up layers from jack platforms and form the structure beginning with the foundation in a compressed arch. The PSU Structural and Materials Analysis Report attached to this Study contains supporting detail in this regard.

<u>Example of 3DCP in Nome Region</u>

Due to Alaska's vast geographic size, extreme variations in climate, diverse geology, limited transportation system, and significant rural housing needs, a market analysis and site analysis can be used to determine most needed and suitable sites for 3DCP construction. An example site is used to clarify site operational details that vary across the State. Based on the potential market demand and rural characteristics, Nome Census Area is used as the example to implement 3DCP that can be copied and modified to other areas of Alaska. Nome is an especially relevant example in this case, since, as shown in Task 5 of this Report, the cost of conventional construction is about 70% more expensive than Fairbanks, which is used as the baseline for comparing the relative cost of conventional construction to 3DCP. Based on the analysis in Task 5 of this Study, the cost of conventional construction for the outer shell of a 1200 square foot house would be about 4x that of the same house constructed by 3DCP. The difference in cost between conventional construction and 3DCP in Nome would be significantly greater.

<u>Market Analysis to Determine Demand / Need</u>: According to the U.S. Census Bureau 2019, the population of the Nome Census Area is 10,004 and according to the U.S. Army Corps of Engineers Nome Seaport Environmental Impact Statement estimate of required workers, the population of the Nome Census Area will almost double if the seaport is expanded and require as many as 3,000 additional houses. To meet this estimated market analysis need, 3DCP can build ten times or more houses compared to conventional construction per year and at a lower cost per square foot (see Task 5 of this Study for details).

Additional market analysis can be done to determine need for more improved housing. For example, approximately one third of Nome's housing is 40+ years old and inadequate due to lack of plumbing.

<u>Site Analysis for Access to Market and Materials</u>: Following the market analysis used to select the Nome Census Area market, site analysis is used to determine an appropriate site to build on. An optimal site serves market demand and minimizes transportation costs of required and available resources. The major ingredient for 3DCP is aggregate refined to less than 3mm from sand, gravel or rock. According to Alaska Department of Transportation and Public Facilities Material Site Inventory, in the Nome Census Area there is a permitted 200m diameter rock quarry (borrow pit) accessible by road a few miles southeast from the City of Nome. A 3DCP construction site near the borrow pit and not far from the Nome housing market demand would minimize transport costs and time for construction while serving market demand. Near the borrow pit the Nome River supplies sufficient water for making concrete mix.

Transportation: Like many Alaska rural communities Nome has a small airport, and it also has a seaport to transport in the 3D printer and other needed equipment and resources. Depending on the type of 3D printer selected, it can be transported to Nome by airplane or ship or barge from Anchorage or Seattle. Most needed equipment and Portland Cement can be rented or acquired in Nome or transported from Fairbanks.

Labor Supply: According to the U.S. Census 2019, Nome Census Area has a labor force of approximately 6,500 persons; and a 2020 unemployment rate of approximately 9.5%. Also, the University of Alaska Fairbanks ("UAF") has a satellite campus in Nome with a construction technology program. The UAF construction technology program emphasizes experiential (hands-on) learning. Nome's available labor plus the possibility to use UAF construction technology student internships and graduates provides an adequate supply of local labor. For 3DCP, no more than five persons are necessary to operate the 3D printer. The Nome labor supply and UAF construction technology program can also provide labor for the interior construction of 3DCP houses.

Project Scheduling: The last frost day is a milestone to start 3DCP of a structure. In Nome's case, the last frost day is estimated to be June 30 (see Figure 9). Prior to that date is the time to acquire any required government permits, transport equipment and materials, deploy and train crew, clear and level the construction site, assemble 3D printer (in less than one day according to 3D printer manufacturers), and prepare concrete mix. Several of the preparation tasks can be done simultaneously. The exact duration of each task will vary according to the location of the site. For example, the site requires a government permit or not, or the site has tree coverage or not, etc. Weather affects any outside construction site project task duration. According to 3D printer manufacturers and experiences by 3DCP expert users (ICON firm and others) the time required to 3DCP exterior of a house is less than 24 hours. Following 3DCP exterior construction, interior construction can proceed with little affect by weather.

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TASK 2 RESEARCH AND ANALYSIS FOR 3D PRINTING COMPANIES

This Section of the Study includes the following components: 1) a description of the gantry and robotic arm styles of 3D concrete printers ("3DCPs") and how they work; 2) a description of 3D concrete printing materials; 3) a survey and comparison of the leading 3DCP firms, the printers they have developed, and their experience in printing houses and other structures; 4) comparison of key characteristics of the 3D printers surveyed; and 5) considerations for the selection of a suitable 3D concrete printer for construction of housing in rural Alaska.

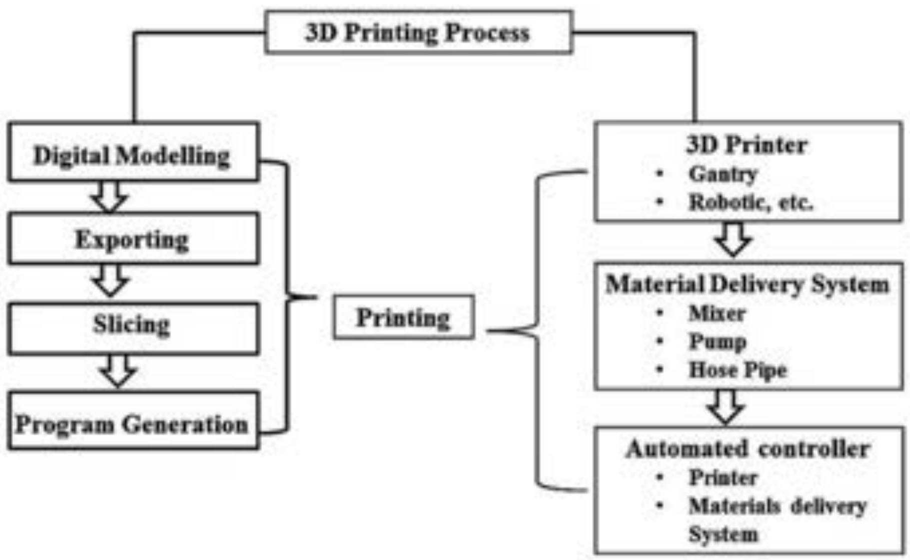
Description of 3D Concrete Printing and the Different Types of 3D Concrete Printers

Additive Manufacturing, also referred to as "3D Printing", is defined as the process of making an object from a three-dimensional model by adding thin layers of material on top of each other (El-Sayegh, 2020). 3D Concrete Printing ("3DCP") is the application of this process to the construction industry, using some form of concrete mixture as the printing material. 3DCP has evolved over the past 20 years with the development of two different technologies: powder-based and extrusion-based. Powder-based 3DCP involves the spreading of a thin powder layer, spraying it with binder droplets, drying the combined mix, removing the unbound powder, and repeating the process, layer by layer. Extrusion-based 3DCP involves extruding a cement-based material through nozzles of different sizes, also to form a layered structure, such the foundation, walls and / or roof of a house, building or other structure (Valente, 2019). This Study focuses on the extrusion-based approach because it is currently the most common with respect to use in the construction industry.

The 3DCP process for housing construction involves both software and hardware components, as well as the material to be printed. The software component consists of 3D Computer Aided Design (CAD) software to design / model the spatial dimensions of the house, Business Information Modeling software, which begins with the 3D CAD design / model and enables document management, coordination and simulation during the entire lifecycle of a project (plan, design, build, operation and maintenance), and slicing software, which "slices" the 3D design of the structure to define the size of each layer and then converts it to the machine language recognized as printing instructions by the 3D concrete printer.

The hardware component consists of a printer which “extrudes” or deposits the concrete material precisely, layer by layer, a material delivery system, which sends the concrete material to the print-head through a mixing and pumping system, and a controller which monitors and controls the printer, mixer and pump according to the design of the structure to be constructed. (Valente, 2019).

Figure 16: Diagram of 3D Concrete Printing Process



Journal of Composite Sciences, 14 Sept. 2019

Since the 3D CAD design has the spatial coordinates of the house, and feeds these coordinates to the printer, the printer can turn on and off the extrusion of print material, placing material exactly in the specified locations. Different materials can be used in the mix to enhance the characteristics of the concrete include thermoplastics, timber, carbon and glass fibers composites, polyurethane, metal weld, and other hybrid materials (Truong, 2019).

There are two main types of 3D concrete printers being developed for use in the construction industry. One is a gantry system, which comes in rail and fixed framework versions. The other is a robotic arm, which comes in fixed and mobile versions. Both types are connected to mixers, pump systems and controllers, and both build structures from the bottom up, placing layer upon layer of concrete or mortar in a pattern directed by the 3D CAD file input.

The gantry system follows the Cartesian coordinate system where the nozzle of the printer moves in three axes (X, Y, Z). The printer operates in three dimensions, with the print head moving back and forth on the X-axis. The X-axis moves along the Y-axis, and the Y-axis moves up and down on the Z-axis columns. In addition to the three axes, the printer head can rotate around the Z axis. This extra degree of freedom is used to rotate the nozzle when the print head changes direction, allowing the nozzle to remain tangent to the tool path, and avoid twisting of the extruded concrete material. The gantry system can be fixed or operate on rails. The gantry principle allows the printer to access any position within the print envelope and gives complete freedom of movement within the reach of the printer, also known as the printable area. Within the printable area, an entire building can be printed with only one set up of the printer, and no need to move and calibrate the printer while constructing the building (BOD 2 Specifications). Examples of companies who have developed gantry-style printers for use in the construction industry include: BeMore3D (Spain), BetAbram (Slovenia), COBOD (Denmark), Contour Crafting (United States), CyBe (Netherlands), Icon (United States), MudBots (United States), SQ4D (United States), Total Kustom Rudenko (United States), Twente-AM (Amsterdam) and WASP (Italy). These companies and their printers are described in more detail later in this Section.

Figure 17: Example of Gantry-Style Printer

The robotic arm printer system can take the form of an off-the-shelf 6-axis robotic arm, or a custom-made arm such as the cylindrical robot manufactured by Apis Cor. In either case, the robot arm has several joints enabling it to telescope and rotate with multiple degrees of freedom, and a rotating printer nozzle attached to the end. The flexibility of the arm allows it to expand its reach and to change the orientation of the nozzle when executing complex printing during the construction process. The print nozzle is connected to the concrete mixer through a hose pipe. A pumping system allows the mix to be transported from the mixer to the print head. The robotic arm is either mounted on a platform that is fixed to the ground, or mounted to a mobile platform (e.g., a rugged motorized vehicle base with tank tracks), enabling the robot to move around the structure being printed, and around the construction site, as necessary. Examples of companies who have developed robotic arm-style printers for use in the construction industry include: Apis-Cor (United States), BatiPrint (France), Constructions-3D (France), CyBe (Netherlands), Hyperion Robotics (Finland) and XtreeE (France). These companies and their printers are also described in more detail later in this Section.

Figure 18: Example of a Robotic Arm-Style Printer

Description of 3D Concrete Printing Materials

There are important differences in the aggregate mixture used in 3D concrete printing as opposed to traditional construction where forms are used to ensure setting and curing of the concrete. Mixtures suitable for 3D printing must have properties to ensure an optimal deposition process: ease of extrusion through the nozzle, maintaining the shape after deposition, good adhesion between the printed layers and satisfactory stacking without collapsing. The curing process takes place without the benefit of molds or containment structures and must not result in any post deposition deformities.

The optimum printable mixture depends on four parameters: extrudability, flowability, open time and buildability. Extrudability refers to the material's ability to be pumped out smoothly through an extruder without any disruption or clogging of the pipe flow. It depends on the mixture composition, nozzle geometry, extruder design and pumping system. Flowability refers to the easy-flowing of the concrete mixture through the printing nozzle without discontinuity. Buildability refers to the ability of the printed concrete layer to hold the layers above other layers without losing its shape or collapsing. Open time refers to Studying the change of concrete flowability over time. The objective is to guarantee that each printed layer can hold itself and begin to harden when poured but remain fluid enough to bond with the layer above it.

Some of the most promising developments for 3D printing in the construction industry are expected to come from materials research, which is focused on the use of numerous types and combinations of raw materials intended to provide additional functionality for 3D printed structures. Areas of focus include: the addition of different types of fibers (e.g., polymers, ceramics, hemp, etc.) to improve the flexural strength and cracking resistance of printed structures; "Green" cement materials (i.e., industrial wastes whose use will reduce consumption of natural resources, energy and resulting in less pollution) without sacrificing compression or tensile strength; fillers (such as recycled tire rubber, plastics, textile waste, paper pulp, etc.) that can be added in partial replacement of local geologic materials to optimize properties of the mixture such as density, thermal insulation, sound insulation, minimization of condensation, and damping of the mechanical vibrations. The addition of chemical additives to the mix may also result in enhanced functional properties, such as self-sensing, self-compacting, self-healing, and self-cleaning. Additional research is focused on decarbonization strategies with respect to cement production, using substitutes such as fly ash or geopolymer-based materials (Valente, 2019).

Leading 3DCP Firms, Their Printers, and Experience Printing Houses

3D printing has taken its first steps into the mainstream of the construction industry, with an explosive number of private sector and university-driven initiatives, strategic participation by established industry players, and a significant and increasing amount of private sector capital coming into the sector. The following is a summary of salient information regarding seventeen leading printer companies from around the world and the printers they have developed. This information reflects what was available to collect during the research phase of this Study. Information was collected mainly from company websites and other information available online, and where possible interviews with company officials.

Companies were not visited due to the COVID Pandemic. This is a highly dynamic and competitive industry, and companies carefully guard information that could be competition sensitive, so publicly available information is limited. This Study intentionally avoided entering into Non-Disclosure Agreements with any company to avoid inadvertent public disclosure of proprietary information. For these reasons, the information collected may not accurately or completely reflect current status of any company's technical and operational capability, experience, plans or business model. Nevertheless, the collected information is as objective as possible based on the public information.

1. Apis-Cor

Figure 19: Images and Summary of Apis-Cor Printer Characteristics

Company Location:	United States
Date Started:	2014
Website:	https://www.apis-cor.com/
Printer Type:	Robotic Arm
Printer Availability:	For Sale
Indicative Pricing:	$300,000 +
Maximum Build Size	8.5m x 1.6m x 1.5m
Printer Dimensions:	TBD
Printer Weight:	1814 Kg (4,000 lbs)
Power Requirements:	8 kW
Printing material:	Proprietary
Setup Time:	Takes less than one hour to set up on site

Company Background: Apis-Cor is a Russian robotic construction company established in 2014, with US operations based in Boston, Massachusetts. The Company has developed specialized equipment for printing building structures on-site in hot and cold-weather climates. Their stated mission is to develop fully autonomous equipment that can print buildings on Earth and beyond (Apis Cor, 2021)

Printer Description: Apis-Cor uses a robotic arm-style 3D printer.

Construction Material: Apis-Cor uses a proprietary mix for its concrete printing material. The mix includes environmentally friendly geo-polymers that are intended to increase the strength and reliability of the structure and reduce the need for industrial additives used in concrete 3D printing.

Transportability: The printer weighs approximately 1814 kg and is relatively compact when disassembled for transport. All the machine-components have a maximum length of three meters so that they can be easily loaded on a truck, trailer, plane, ship or barge, and be transported.

On-Site Construction Capability: Apis-Cor's 3D printer equipment is designed to operate in harsh environments with wide variances in temperature and humidity during the course of the same construction (Apis-Cor, Achieving the Impossible, 2021). Its design enables building directly on-site without any extra assembly works. The printer is mobile and can be moved around the construction site to print larger structures. It features a stabilization system and mobile automated, self-cleaning mix and supply unit and control program to facilitate the construction work. It can cover a total area of 132 m^2, creating walls layer-by-layer using the mixed concrete. The stabilization system enables it to be installed on almost any surface with less than 10 cm of elevation difference.

Demonstrated Capability: Apis-Cor built its first full-scale house in Russia in 2017. The house was erected in the middle of winter. While the use of concrete mixture is only possible at temperatures above freezing, Apis Cor says their equipment can operate in temperatures down to minus 31° Fahrenheit. Apis-Cor solved the problem of on-site printing in below-freezing temperatures by setting up a tent that provided the required heating and protection from precipitation during the period of construction (Apis-Cor Prints 1st House In One Day, 2017). Then in 2019, Apis-Cor went to the opposite extreme and printed a two-story office building in the hot climate of Dubai. The building measured 9.5 meters height with a floor area of 640 square meters. The Company says it took a total of

17 days to print the building with a gypsum-based material (Apis-Cor Collaborates on World's Largest 3D Printed Building, 2019). Apis-Cor and the Housing Trust Fund of Santa Barbara County are collaborating to develop a prototype 3-D printed affordable home in or near Santa Barbara County. As an interim step, they have received a building permit from the City of Colida, California for a one-story 3D concrete printed home and are looking for a piece of land to build on (Housing Trust Fund of Santa Barbara County, 2019). The Company is also building affordable housing in the State of Louisiana (Cheniuntai Changes the Future with Apis-Cor, 2021). It has also been an active participant and won several awards in NASA's "3D-Printed Habitat Challenge" for Moon / Mars habitats. The goal of the 3D-Printed Habitat Challenge is to foster the development of new technologies necessary to 3D print a habitat using local indigenous materials with, or without, recyclable materials (NASA Update, 2019). These same capabilities can be used to produce affordable housing on Earth where access to conventional building materials is limited.

Apis-Cor is focused on developing 3D printed structures that are directly comparable to the well-documented and accepted reinforced Concrete Masonry Unit ("CMU") wall. By matching its 3D printed walls with the CMU wall all construction techniques employed in roofing, foundation, etc., can be the same as used for CMU (Apis-Cor, 3D Printed Structures as Comparable to Masonry Construction, 2019).

2. Batiprint3D

Figure 20: Images and Summary of Batiprint3D Printer Characteristics

Company Location:	Nantes, France
Date Started:	2019
Website:	http://batiprint3d.fr/en/
Printer Type:	Robotic Arm
Printer Availability:	Sale or Lease
Indicative Pricing:	$300K
Maximum Build Size:	No limit in W and L - 4,70 m H without any lifting mean
Printer Dimensions:	TBD
Printer Weight:	907 Kg
Power Requirements:	20 kW
Printing material:	Proprietary
Setup Time:	Less than 1 hour with 2 people

Company Background: BatiPrint3D originated from work conducted by professors and researchers from two laboratories at the University of Nantes: the Laboratory of Digital Sciences of Nantes, specializing in the development of robotic systems, and the Research Institute of Civil Engineering and Mechanics, specializing in materials science (Batiprint3d, 2021).

Printer Description: The printer is a robotic arm on a mobile cart. Placed on an automated guided vehicle it can adapt to environmental conditions at the construction site and is stable enough to allow controlled extrusion of the material.

Construction Material: The Batiprint 3D printer has the ability to print 3 layers at once: a middle layer of concrete and inner and outer layers of polymeric foam that serves as formwork for the concrete. The polyurethane mold is printed first, and then infilled with concrete to achieve structural strength and insulation. Once the elevation walls are finished, the foam remains in place as insulation for the home without thermal bridges.

Transportability: The printer is relatively lightweight with dimensions that it easy to transport.

On-Site Construction Capability: The printer is designed to operate outside at a construction site, in a wide range of environmental conditions.

Demonstrated Capability: Batiprint3D made international headlines when completing its “YHNOVA” 3D printed house in Nantes, France. The YHNOVA house is equipped with multiple sensors and home automation equipment in order to assess and analyze the behavior of materials, thermal quality and acoustics, during the 1st year post-completion. YHNOVA will serve as a place of education and meetings with professionals and residents. The house will eventually be rented to a family selected by the University according to its criteria for social housing (YHNOVA Presentation, 2020). Additionally, Batiprint also plans to print in Beaucouzé, in Anjou a single-family house on behalf of the builder ERB, based in Chalonnes-sur-Loire. The Company has another project to print nine social housing units for a social landlord in Anjou. Additionally, the Parisian developer Compagnie de Phalsbourg has contracted with Batiprint for its Atoll shopping complex (91,000 m²), near Angers (Batiprint Press Kit, 2020).

3. BeMore3D

Figure 21: Images and Summary of BeMore3D Printer Characteristics



Company Location:	Valencia, Spain
Date Started:	2017
Website:	https://bemore3d.com
Printer Type:	Gantry System
Indicative Pricing:	TBD
Maximum Build Size:	TBD
Printer Dimensions:	TBD
Printer Weight:	800 kg
Power Requirments:	6 kW
Printing material:	Proprietary
Setup Time:	Assembled and disassembled in 4 hours using 3 workers;

Company Background: BeMore3D is a Spanish startup, based in Valencia, focused on improving and implementing 3D printing technologies in construction (BeMore3D, 2021).

Printer Description: The BEM PRO printer is a gantry-style 3D printer (Be More 3D, The Printing Industry's Technology 4.0, 2018).

Transportability: The Company says its 3DCP printer has an easy assembly system making it ideal for transport and manufacturing houses in remote areas with little or no infrastructure.

On-Site Construction Capability: The printer is installed on a previously created foundation slab, on top of which the building will be printed. The BEM PRO printer has been designed to be modulated in both the horizontal and vertical axes enabling adjustment of the dimensions of the construction. Further, one axis is mounted on motorized wheels to enable horizontal movement in an unlimited manner. This will enable creation of an adjacent building without having disassemble the printer. According to BeMore3D, the device can operate in extreme heat and humid conditions.

Demonstrated Capability: In 2019, it showcased its technology at the first edition of the "Solar Decathlon Africa," printing a 32 meter^2 house in 12 hours and won the most innovative startup award. The Company also printed a 24 square meter house in Spain, in collaboration with the Polytechnic University of Valencia.

4. Betabram

Figure 22: Images and Summary of Betabram Printer Characteristics

Company Location:	Slovenia
Date Started:	2012
Website:	https://betabram.com/
Printer Model:	Betabram P1
Printer Type:	Gantry System
Printer Availability:	For Sale
Indicative Pricing:	> $300,000 USD
Maximum Build Size:	8m x 14m x 2.5m
Printer Dimensions:	9m x 16m x 3.5m (Width x Length x Height – largest model P3)
Printer Weight:	500 Kg.
Power Requirements:	4 kW
Printing material:	Non-Proprietary
Setup Time:	TBD

Company Background: Betabram is a Slovenian company founded in 2012 focused on the development of 3D printing technology and gantry-style machines. Betabram began offering 3D printers for sale in 2013 and has continued to develop its technology and products since then (Betabram, 2021).

Printer Description: The printer is a gantry-style printer.

Construction Material: Betabram uses a cement-based material that could generally be considered a mortar, based on the aggregate composition. The aggregate is very fine, mostly sand approximately up to 2mm in size. According to the company the mix ratios are very close to shotcrete mixtures, which means high cement content and very small aggregates. This makes the material a very fluid paste that is easy to spread and shape on the printing surface. The material is also mixed with additives provided by KEM, a local chemical and sand aggregate production company from Slovenia.

Demonstrated Capability: Betabram is printing a house in Slovenia that is 10m x 8m. This is providing the Company much needed experience in winter construction.

5. Black Buffalo

Figure 23: Images and Summary of Black Buffalo Printer Characteristics

Company Location:	New York, USA
Date Started:	2020
Website:	https://www.blackbuffalo.io/
Printer Model:	NEXCON 1 and NEXCON 2
Printer Type:	Gantry System
Printer Availability:	Sale, Lease, Manufacture
Indicative Pricing:	NEXCON 1: $400,000 +; NEXCON 2: $700,000 +
Maximum Build Size:	NEXCON 1: 13ft x 8ft x H7.2ft; NEXCON 2: 39ft x 39.4ft x H39ft
Printer Dimensions:	NEXCON 1: 20ft x 11ft x H11.5ft; NEXCON 2: 46ft x 46ft x H46ft
Printer Weight:	TBD
Power Requirements:	TBD
Printing material:	Proprietary
Setup Time:	TBD

Company Background: Black Buffalo is a global provider of large-scale 3D printers for construction and proprietary cement-based ink. Based in New York, USA, it is the U.S. affiliate and global sales and distribution arm of HN Corp., formerly Hyundai BS&C Co. Ltd., under Big Sun Holdings Group, Inc. It also has its own engineering team and factories. According to Peter Cooperman, Head of Marketing, the Company's overarching mission is to provide scalable 3D construction printers and cement-based inks through partnerships in the construction, development and tourism sectors. Black Buffalo's 3D printing technology is designed to print houses, commercial buildings, temporary and permanent structures and sculptures more efficiently, affordably and sustainably.

Printer Description: Black Buffalo is currently marketing two gantry-style printers developed by its sister company, HISYS— based in South Korea: NEXCON 1: which specializes in 1-4 story affordable houses and can print over 1500 square feet with extension ability depending on the design requests; and NEXCON 2, which specializes in 4 story commercial buildings and can print over 1,550 square feet with extension ability depending on the design requests.

Construction Material: Black Buffalo has developed a wide variety of proprietary ink material for 3D printing.

On-Site Construction Capability: Black Buffalo gantry-style printers have the ability to print onsite & custom designs.

Demonstrated Capability: Black Buffalo has partnered with tourism and resort company LTG, to build tiny "tredee" house condo resorts in multiple locations around the world. The first development was announced in September 2020. Both companies are currently working together to fine tune the 3D printing technology and materials as well as the tredee design. The launch of a test print in the U.S. occurred in 2021 (with ongoing tests being carried out in South Korea). Black Buffalo has also entered into a long-term strategic financial relationship with Ethos Asset Management, which will provide Black Buffalo the capital necessary to expand its manufacturing of 3D construction printers, production of cement ink and development of blockchain-based IoT (Internet of Things) solutions to match international demand.

Building Codes: Black Buffalo is investing in its 3D construction printers and material science with the intent to become the first 3D construction printing company to meet ICC-ES AC509. 3D Corporation is working with the International Code Council Evaluation Service (ICC-ES) to revise its ICC-ES AC509 criteria. ICC-ES is a nonprofit, limited liability company that performs technical evaluations of building products, components, methods, and materials. Agencies use evaluation reports to help determine code compliance and enforce building regulations; manufacturers use reports as evidence that their products (and this is especially important if the products are new and innovative) meet code requirements and warrant regulatory approval. As a globally recognized organization, ICC-ES brings legitimacy to code compliance claims and helps developers ensure building regulations are met.

6. COBOD

Figure 24: Images and Summary of COBOD Printer Characteristics

Company Location:	Denmark
Date Started:	2015
Website:	https://cobod.com/
Printer Type:	Gantry System
Printer Availability:	For Sale
Indicative Pricing:	$600K + ($375K for printer only)
Maximum Build Size:	9m H x 12m W x infinite long
Printer Dimensions:	2.5 m modules; expandable up to 6 modules
Printer Weight:	4,500 Kg
Power Requirements:	25 kW for printer; 50 kW if batching plant used in combo
Printing material:	Non-Proprietary but COBOD recommends using its own mix
Setup Time:	One day to set up

Company Background: COBOD is a Danish 3D printing construction company, established initially as a 3D printing reseller, service provider, and developer. The German PERI Group, which is the world's largest manufacturer and supplier of formwork and scaffolding systems, has acquired a significant stake in COBOD (COBOD, 2021).

Printer Description: The BOD2 3D printer is a gantry-style system that can print buildings with measurements of 12m in width, 27m in length, and 9m in height. The size can be extended with modules in width, length, and height of 2.5 meters. Its maximum capacity can accommodate six modules for width equaling 15 meters, and four modules in height, coming up to 10 meters, with no restrictions for length. The BOD2 can produce three-story buildings in one go, with each story capable of being more than 300 square meters in length (BOD2 Specifications, 2020).

Construction Material: The BOD2 has been developed to print with a wide range of materials. While the Company has developed its own proprietary mix and recommends its use, the warranty is not voided if non-proprietary mix is used instead. The extruder can handle aggregates with particle sizes up to 10 mm, and thus print with real concrete and not just mortars (BOD2 Brochure, 2020). The cement, sand and gravel and other ingredients are mixed together on site, which can be done with manual equipment or via automatic mini batching plants, which COBOD offers. This process is more complex than relying on ready mix mortars, but at a fraction of the cost.

<u>Transportability</u>: The Company states that the BOD2 printer is easily transportable, with the maximum length 8.3 feet for any of its components. With just 2-3 people, the printer can easily be assembled, disassembled and moved with a truck. Once on the construction site, it can be moved from one building location to the next.

<u>On-Site Construction Capability</u>: The BOD2 is designed for on-site printing. When printing on an uneven or poorly levelled surface, the printer measures the distance to the foundation and collects the data in a "height map". When printing the first layers, the printer can automatically compensate for these uneven surfaces, layer by layer, until the resulting print is completely level.

<u>Demonstrated Capability</u>: In 2017 COBOD 3D printed the first building in Europe – The BOD ("Building-On-Demand"). The building was consistent with European building codes. In 2019, Saudi Arabia purchased a modular printer from COBOD large enough to print three story buildings of more than 300 square meters per story. Also, in 2019, COBOD delivered 3D construction printers to Belgian Kamp C, German Peri Group, Danish Technical University and Saudi Arabian Elite for Construction & Development. COBOD is now producing its printers and distributing them worldwide. In addition, PERI Group also began distributing the COBOD 3D construction printers in the German-speaking part of Europe. COBOD tripled its order intake in 2020 (COBOD and PERI, 2020).

7. <u>Constructions-3D</u>

Figure 25: Images and Summary of Constructions-3D Printer Characteristics



Company Location:	France
Date Started:	TBD
Website:	https://en.constructions-3d.com/
Printer Type:	Robotic Arm
Printer Availability:	For Sale
Indicative Pricing:	> $550,000 USD
Maximum Build Size:	9.5m x 9.5m x 3.3m
Printer Dimensions:	13m x 13m x 3.8m
Printer Weight:	2500 kg
Power Requirements:	7 kW
Printing material:	Proprietary
Setup Time:	Several hours with 2-3 people

Company Background: Constructions-3D is a subsidiary of Machines-3D, a reseller offering a range of 3D printers, 3D printing materials and accessories. (Constructions-3D, 2021).

Printer Description: Robotic arm built on the model of a lifting hydraulic crane (Technical Documentation, 2021).

Transportability: The printer can be folded for easier transportation. It is delivered with its 20-foot container and all the accessories needed for it to work (e.g., pumps, software) as well as a training session.

On-Site Construction Capability: The printer is a robust, transportable machine capable of printing structures on site.

Demonstrated Capability: Constructions-3D has announced its success in printing the "Pavilion", the first printed concrete construction in France, and is now planning to 3D print the premises of its future headquarters. Ultimately, 2,200 m2 will be printed in concrete on site in Bruay-sur-l'Escaut.

8. Contour Crafting Corporation

Figure 26: Images and Summary of Contour Crafting Printer Characteristics

Company Location:	United States
Date Started:	2014
Website:	http://contourcrafting.com/
Printer Type:	Gantry System
Printer Availability:	For Lease
Indicative Pricing:	TBD
Maximum Build Size:	TBD
Printer Dimensions:	TBD
Printer Weight:	< 1,000 Kg
Power Requirements:	TBD
Printing material:	Proprietary Quikrete formula
Set Up Time:	1-2 people

Company Background: Contour Crafting Corporation (CC Corp) was founded by Dr. Behrokh Khoshnevis in collaboration with international partners. According to the Company, there are more than 100 US and international patents on various aspects of Contour Crafting and other technologies which have been licensed to CC Corp by the University of Southern California. CC Corp has received numerous awards for its 3D printing technology, including the grand prize by NASA Tech Briefs Media Group in November 2014 and another NASA international competition Grand Prize in 2016 (Contour Crafting, 2021).

Printer Description: Gantry-style (Contour Crafting, 2021).

Construction Material: CC Corp recently announced a partnership with QUIKRETE to utilize proprietary concrete mix specially formulated to work with the CC Corp 3D printing system. The mix includes a coarse aggregate and additives to provide rapid-setting and dimensional stability features.

Transportability: The Company has developed a rapidly deployable and truck transported printer model, referred to as “CraftTrans”, designed, built and delivered in 2020 under contract to the US Army Corps of Engineers, Construction Engineering Research Laboratory for expeditionary response. The printer can be unfolded, operated and then re-folded for truck pick-up by 1-2 persons.

Demonstrated Capability: In addition to its development contract for the US Army Corps of Engineers, CC Corp was selected in June 2020 by the Los Angeles County Development Authority (“LACDA”) to use construction 3D printing for affordable housing. CC Corp, in collaboration with the design firm HDR and Volunteers of America Los Angeles (“VOALA”) is tasked with building four low-income housing units at a designated site in LA County. The Demonstration Project to Fast-Track Housing Supply will test, contextualize, and add to the LACDA’s existing affordable housing ecosystem by utilizing forward-thinking technology and methodology. CC Corp has also played a major role in the effort for building code acceptance of construction-scale 3D printing. (Contour Crafting Announcements, 2020).

9. CyBe 3D Construction

Figure 27: Images and Summary of CyBe 3D Construction Printer Characteristics

Company Location:	Netherlands
Date Started:	2013
Website:	https://cybe.eu/
Printer Model:	CYBE RC 3DP, CYBE, CYBE G 3DP, CYBE GR 3DP
Printer Type:	Robotic Arm, Gantry and Hybrid models
Printer Availability:	For Sale
Indicative Pricing:	$250K (Robotic Arm), $185K (Gantry), $400K (Gantry + Robot),
Maximum Build Size:	2.5m x 5.0m x 4.0m
Printer Dimensions:	Robot: 2.5x3x4 m; Gantry: 5x5x2.5 m; Hybrid:6x6x3.25 m
Printer Weight:	Robotic Arm: 3,500 kg; Gantry and Hybrid Models TBD
Power Requirements:	8 kW
Printing material:	CYBE's patented mix preferred; not required
Set Up Time:	2 hands-on operators

Company Background: CyBe was founded in 2013 to develop 3D robotic printing capabilities for the construction of houses, buildings and other structures, as well as the development and sale of the 3D printers. CyBe began securing construction projects in 2016, and in 2018, it delivered its first printer to a customer in Japan. According to its Founder and CEO, Berry Hendriks, by 2020, the company had five machines in operation around the world—in Morocco, Spain, UAE (Sharjah), Japan and the Netherlands and five more under contract, with an even larger sales pipeline through the end of 2021 (Just CyBe, 2020).

Printer Description: The CyBe robot 3D printer is available in several different configurations: mobile robot arm, fixed gantry and hybrid gantry / robot arm.

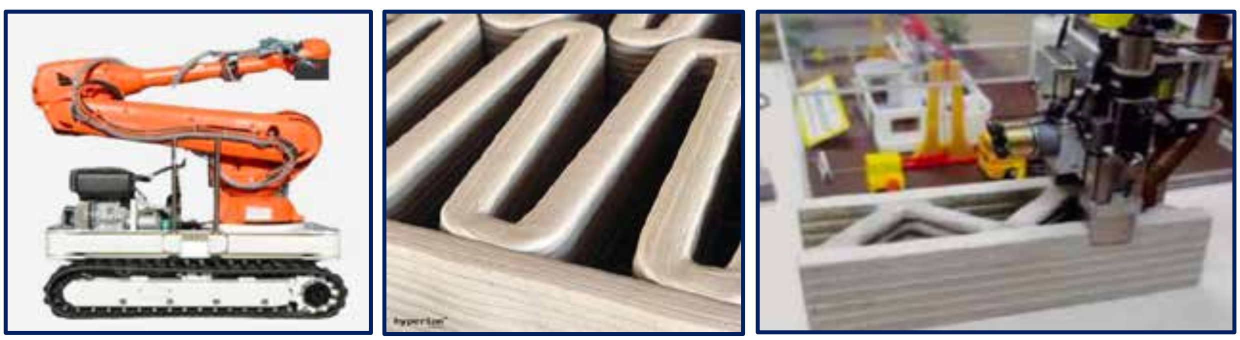
Construction Material: "CyBe Mortar" is the Company's proprietary. high-performance, single-purpose material specially developed for 3D concrete printing applications. Durable in all environments, CyBe Mortar is non-metallic with a very low chloride and sulphate content. CyBe advises its customers to use Cybe Mortar with its 3D concrete printer to produce high durability objects where low shrinkage is desired. CyBe Mortar sets in 3 minutes and achieves structural strength in 1 hour.

On-Site Construction Capability: CyBe's mobile printer is an off-the-shelf ABB Inc. robotic arm placed on a mobile crawler with tank tracks. It can roam freely around a construction site and be used for various other applications like abutments, floors, walls, formworks, and sewer pits. Its extendable hydraulic feet give the printer stability during printing and increase the total printable height. The advantages of using a robotic arm on a mobile platform are variable square footage, a robotic wrist to print at angles, and mobility of on-site construction. Having a variable square footage building is useful when printing multiple structures and building products at multiple points on a construction site.

Demonstrated Capability: CyBe has printed a number of buildings, including: the 1st approved 3D printed building in the UAE by the Municipality of Dubai (2017); the De Vergaderfabriek building, which is a 100 square meter hotel in Europe that allows guests; the "La Sphère" guard house, located at the heart of the residence "Maréchal de Lattre de Tassigny" of Immobilière Basse Seine, a residence in Harfleur of 180 social housing units (CyBe Cases, 2021), and an eight story apartment complex in India. The Indian customer purchased the 3D printer and hired CyBe's team in the Netherlands to design and engineer the apartment complex, and to develop the cement mixture for the building to include local materials from India (Just CyBe, 2020). CyBe also has projects in Indonesia, Mexico, Paraguay, Middle East, Japan and New Zealand.

10. Hyperion Robotics

Figure 28: Images and Summary of Hyperion Robotics Printer Characteristics



Company Location:	Helsinki, Finland
Date Started:	2019
Website:	https://www.hyperionrobotics.com/
Printer Type:	Robotic Arm (Kuka)
Printer Availability:	Sales, rental and project services
Indicative Pricing:	$350K +
Maximum Build Size:	Mobile + 2 times (5m x 2m x 2m)
Printer Dimensions:	3m x 2.5m
Printer Weight:	1,450 Kg
Power Requirements:	15 kW
Printing material:	Hyperion mix is recommended and can be supplied and licensed; not required
Set Up Time:	less than 1 hour

Company Background: Hyperion Robotics (Hyperion) was founded in Helsinki by a team of academics and professionals in robotics, architecture and engineering. Its mission is to revolutionize the construction industry by using 3DCP technology to produce reinforced concrete elements faster, cheaper, safer and more environmentally friendly. The company has developed an end-to-end 3DCP solution which includes its advanced printing head and proprietary control software mounted to a large-scale industrial robotic arm (Hyperion Catalogue of 3D Printers, 2021). Hyperion Robotics uses a Kuka robotic arm in its projects, but the Company maintains that it is "robot agnostic." Hyperion is developing and integrating its own proprietary software – which it claims can be used by anybody with no technical background – and 3D printing equipment in different kinds of systems (Hyperion, 2021).

Printer Description: Hyperion's Mobile 3D Concrete Printer includes a Kuka Inc. robotic arm with a radius of 3.9m and robot controller, mounted on an undercarriage, "similar to Caterpillar machines". It comes with an automated pump/mixing system and Hyperion's advanced printing head and 3D printing and control software (Hyperion Catalogue of 3D Printers, 2021).

Construction Material: Hyperion has developed its own proprietary mix optimized for its 3D printing systems that is designed to set and cure faster than regular cement in hot or cold weather. The mix currently includes up to 70% recycled materials (e.g., biochar from agricultural waste, mining tailings, fly ash from coal power plants, blast furnace slag, etc.), and Hyperion is working on ways to increase this amount to 90% while continuing to reduce reliance on cement and to further reduce the carbon footprint. Hyperion will provide customers with the mix or will license the formula to enable customers to make it themselves. Hyperion does not prohibit the use of other concrete mixes from third party suppliers, but it does not guarantee the quality of the results.

Transportability: Hyperion's 3D printer is designed for ease of transport to remote sites. The printer is compactly designed as an end-to-end solution that combines hardware and software (robotic arm on mobile tracks, Hyperion printing head, robot control unit, Hyperion software and laptop and digital mixing pump) within a simple and intuitive interface (Hyperion Catalogue of 3D Printers, 2021).

On-Site Construction Capability: The printer is rugged, weather-proof and designed to be operated by a single person at the construction site.

Demonstrated Capability: Hyperion is collaborating with nonprofit organization Thinking Huts and architecture firm Studio Mortazavi to build the world's first 3D-printed school in Madagascar. Hyperion is also partnering with Thinking Huts, an American NGO that plans to 3D print schools for countries in Africa where there is almost no access to education for the majority of the child population (Hyperion Robotics. 3D printing schools in Madagascar, 2020).

11. ICON

Figure 29: Images and Summary of ICON Printer Characteristics

Company Location:	United States
Date Started:	2017
Website:	https://www.iconbuild.com/
Printer Type(s) for Housing Construction:	Gantry System
Printer Availability:	Sale, lease or project service TBN
Indicative Pricing:	$250,000 + USD
Maximum Build Size:	2.6m (height) x 8.5m (width) Print length is effectively infinite.
Printer Dimensions / Build Capabilities:	3.5m (height) x 10m (width) x infinite length
Printer Weight:	1724 kg (3800 lbs)
Power Requirements:	16 kW
Printing Material:	Proprietary mix "Lavacrete"

Company Background: ICON is a US company started in 2017, whose stated mission is to revolutionize homebuilding, based on sustainable technology and construction innovation, with 3D robotics, engineering, advanced materials and software as the centerpiece. (ICON, 2021).

Printer Description: ICON's Gantry-style Vulcan 3D printer is designed for constructing single story structures up to approximately 2,000 square feet. The Gantry stands 11.5 feet tall and can print wall structures up to 8.5 feet in height. It spans 33 feet in width and can print on foundations up to 28' wide. Print length is effectively infinite. The Vulcan features intuitive tablet-based controls, remote monitoring and support, onboard LED lighting for printing at night or during low-light conditions, and a custom software suite.

Construction Material: ICON says its proprietary Portland Cement-based mix, called "Lavacrete" enables it to rapidly print homes that are aesthetically pleasing, structurally sound and cost effective. ICON represents that Lavacrete has a compressive strength of 6,000 psi, well above the strength of existing building materials, and that it is able to withstand extreme weather conditions to minimize the impact of natural disasters. ICON represents that its material can be sourced from anywhere in the world, and that it can be printed at high speeds while retaining form, enabling homes to be built faster, keeping construction projects on schedule and on budget (ICON, 2021).

Transportability: The Vulcan printer is designed for transport in ICON's custom trailer. The printer is also designed to work under the constraints common in places like Haiti and rural

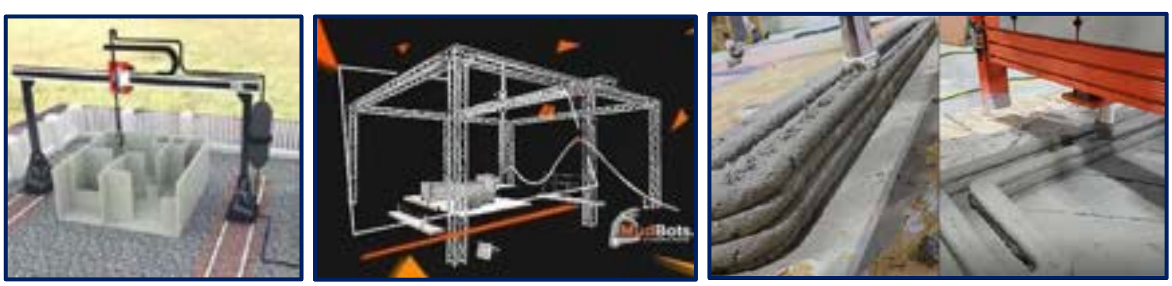
El Salvador where power can be unpredictable, potable water is not a guarantee, and technical assistance is sparse. (ICON, 2021).

<u>On-Site Construction Capability</u>: ICON's printer rails are typically fixed to the edges of a poured foundation. The gantry-printer system rolls off the truck and onto the slab for printing. Printing requires stable temperature. The robot is rugged, built to function in diverse conditions; more like a lawnmower than a racing engine.

<u>Demonstrated Capability</u>: In 2019, ICON printed its 1st 3D housing community in Tabasco, Mexico. In the U.S., the Company completed six 3D printed homes at Community First! Village in Austin, TX, in collaboration with non-profit partner, New Story (ICON + New Story, 2019). The build size of each home was 2,000 square feet. The homes are built to the International Building Code (IBC) structural code standard. ICON is the first company in the United States to get a building permit to 3D print a home in Austin, Texas (BIG Partners Up With ICON, 2020). It has also completed a series of 3D-printed homes for families as part of a partnership with Mobile Loaves & Fishes (MLF), an Austin, Texas non-profit. (ICON Delivers Homes to Homeless, 2020). Separate from construction of affordable housing on Earth, ICON won an award from NASA for its design of a 3D printed outpost to be built on the Moon or Mars (ICON, NASA Challenge, 2019).

12. <u>MudBots</u>

Figure 30: Images and Summary of MudBots Printer Characteristics



Company Location:	United States
Date Started:	2017
Website:	www.MudBots.com
Printer Type:	Gantry System
Printer Availability:	For Sale
Indicative Pricing:	$175,000 to $2,400,000 USD
Maximum Build Size:	1.83m x 1.83m x 1.22m
Printer Dimensions:	35' to 70' W; 10' H; track: 16'
Printer Weight:	623 kg for 18x18x8
Printing material:	Non-Proprietary
Set Up Time:	2 hours, 2 people to operate

Company Background: MudBots is a subsidiary of USABotics, a manufacturer of industrial robots based in Lindon, Utah, USA. (MudBots, 2021).

Printer Description: MudBots' gantry-style printer comes equipped with pumping system and mixer. Optional equipment includes mobile batch plant, dry mix hopper, vertical mix elevator, additive pre-mixer, geopolymer pumping system, aggregate pumping system and composite pumping system (MudBots, 2021).

Construction Material: Mudbots allows third party mixes for use with its 3D printers. MudBots states that it has tested, and continues to test, different mixes from standard Portland scenarios to hempcrete, clay, polyethylene, polyurethane, geopolymer and geopolycrete, and indicates that a wide range of alternatives are on their way to becoming industry standards. MudBots further states that the strength of Type S Portland cement is about 2500 to 3000 psi which is more than enough for print jobs, but that the addition of other attributes like hardeners, synthetic fibers, polystyrene fillers, powder adhesives, plasticizers, etc., can significantly enhance the mix's characteristics. MudBots provides lab results for several of the most common mix formulas, which are included with the purchase of every machine (MudBots, 2021).

Transportability: MudBots equipment is relatively lightweight and designed for easy transport (MudBots, 2021).

On-Site Construction Capability: MudBot's gantry structure has wheels, enabling it to move from lot to lot (up to 100 yards) in rural areas without dis-assembly. MudBots provide 24/7 "virtual on-site" remote engineering support with real-time, hands-free (see what I see) diagnostics. With the aid of broadband connectivity and vision support equipment worn by on-site personnel, the engineering team at MudBots' headquarters can see everything remotely, and work with on-site teams to trouble-shoot and direct any necessary adjustments or repairs to the equipment as though they were actually there. Implementing remote viewing eliminates costly delays and expensive travel that made remote service so cost-prohibitive in the past (MudBots, 2021).

13. SQ4D

Figure 31: Images and Summary of SQ4D Printer Characteristics



Company Location:	United States
Date Started:	2014
Website:	https://www.sq4d.com/
Printer Type:	Gantry System
Printer Availability:	For Lease
Indicative Pricing:	TBD
Build Capabilities - HxWxL:	9.1m x 4.4m x infinity; 2,000 sq. ft.
Printer Dimensions:	20-feet by 40-feet
Printer Weight:	TBD
Power Requirements:	TBD
Printing material:	Non Proprietary
Set Up Time:	About 6 hours to assemble with 2 people, a Bobcat/Skidsteer

Company Background: SQ4D is a 3D printer manufacturer from Patchogue, NY, that produces a range of 3D printers, including those for construction of homes and other building structures. SQ4D was recognized as the best 3D homebuilder of 2019 with its first of its kind unlimited footprint design called Autonomous Robotic Construction System (ARCS) (SQ4D, 2021).

Printer Description: SQ4D has developed a ruggedized gantry-style printer capable of constructing commercial and residential building structures. The printer is made with aircraft-grade aluminum and stainless steel (SQ4D, 2021).

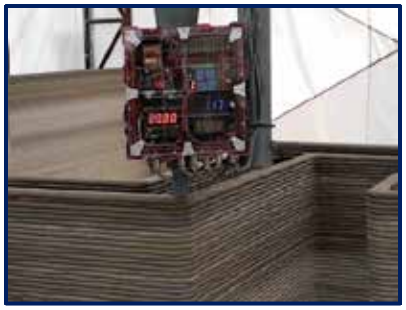
Construction Material: SQ4D uses Portland cement, aggregate and water as its basic print material but does not limit purchasers from using their own mixes. Additives may be used to enhance the characteristics of the cement, depending on requirements of the structure. (SQ4D, 2021).

On-Site Construction Capability: SQ4D's gantry-style printer robotically builds the footings, foundations, interior and exterior walls of residential dwellings on site. The printer system is designed to print in most weather conditions, but the Company recommends against printing in heavy rain or high winds to avoid damage to the concrete during the printing process (SQ4D, 2021).

Demonstrated Capability: SQ4D's first 3D printed home are slated to receive a certificate of occupancy and listed for sale on Zillow.com for $299,999 US dollars. The house has 1,500 square feet of living space (3 BR, 2 Bath, open floor plan), plus a 2 ½ car garage on a ¼ acre. The home comes with a 50-year limited warranty on the 3D printed structure (SQ4D News, 2021).

14. Total Kustom Rudenko

Figure 32: Images and Summary of Total Kustom Rudenko Printer Characteristics



Company Location:	United States
Date Started:	2014
Website:	http://www.totalkustom.com/
Printer Model:	StroyBot and StroyBot Military Grade
Printer Type:	Gantry System
Printer Availability:	For Sale
Indicative Pricing:	$300K to $950K USD
Maximum Build Size	(4)6mx 10m x (15)20m; capable of building 1-2 story houses up to 150 sq. meters for each floor.
Printer Dimensions:	Dimensions: 13x20x7 meters
Printer Weight:	2,268 Kg.
Power Requirements:	1.6 kW
Printing material:	Non-Proprietary
Set Up Time:	Set-up and Take-down time is 60 minutes

Company Background: Total Kustom Rudenko is a company started by Andrey Rudenko, formerly an engineer at Intel, whose mission is to develop robotic systems that facilitate the construction of affordable and smarter housing (Total Kustom Rudenko, 2021).

Printer Description: The Company's gantry-style printer comes with gantry system, extrusion system (print head with nozzle), mobile automated mixing station (screening, mixing), automated raw material feeding system, control box (electronics, positioning, control system), remote control and monitoring system (viewing progress of the print 24/7) and safety system (prevents collision and automatically shuts down as needed) (Total Kustom Rudenko, 2021).

Construction Material: The printer can print with various materials and recipes for making concrete. Materials should be sourced locally. The automated mixing station is included - it will screen materials, mix, and feed the mortar (‘ink') to the print head. No need to buy expensive pre-made mixes. Mixing raw materials right at the job site minimizes cost (Total Kustom Rudenko, 2021).

Transportability: The light-weight mobile printer will fit a truck and can be moved from site to site by a crew manually; it does not require a crane. The printer is capable of operating in a variety of environmental conditions. The system is designed to be highly mobile, to be transported globally via airplane, using DoD or civilian logistics systems. Set-up and take-down time are less than one hour (Total Kustom Rudenko, 2021).

On-Site Construction Capability: The printer is made from Aluminum and Carbon/Kevlar Composite, intended to be rigid, and relatively lightweight for movement at the job site. The system is also rust-proof, which can be a critical advantage for regions with a humid climate. It is designed to operate year-round, in cold Northern countries, hot Middle East climate, and during rainy seasons in Asia (Total Kustom Rudenko, 2021).

Demonstrated Capability: The Company has successfully print validated an assortment of trial structures in concrete, in different climatic conditions, including the world's first 3D-printed concrete castle in the United States and the 3D-printed Concrete Hotel for Lewis Grand in the Philippines (Total Kustom Rudenko, 2021).

15. Twente Additive Manufacturing (TAM)

Figure 33: Images and Summary of TAM Printer Characteristics

Company Location:	Amsterdam
Date Started:	2018
Website:	https://www.twente-am.com
Printer Type:	Gantry System (Cartesian flying gantry system);
Printer Availability:	TBD
Indicative Pricing:	TBD
Maximum Build Size:	9m x 40m x 15m (larger printer "Leonardo" has add'l 2.5 m reach build volume)
Printer Dimensions:	TBD
Printer Weight:	TBD
Power Requirements:	Tbd
Printing material:	Proprietary / Laticrete
Set Up Time:	Less than one day

Company Background: Twente Additive Manufacturing (TAM) is a Dutch start-up focused on architectural 3D printing. Its 3D gantry-style printer was developed and assembled at the company's research and development center in Nelson, Canada (Twente Additive Manufacturing, 2021).

Construction Material: TAM uses a proprietary mortar designed by Laticrete specifically for 3D printing.

On-Site Construction Capability: TAM printed its first 3DCP house at the TAM laboratory / factory to ensure a controlled environment for the construction, where the printer was unaffected by the outside elements and working 24/7. The house is called the Fibonacci house because the printing method relies on the famous Fibonacci Curve to demonstrate the versatility of the technology. An important component of the house is its insulated walls, specifically designed to create a comfortable, thermally insulated environment on the inside of the structure while avoiding condensation in walls and thermal bridging. The insulated walls also hold all the HVAC conduits and infrastructure. The wall shapes are not only in the form of arcs, but the arc radius itself was constantly increased through the architectural layout of the structure. The uniquely shaped walls are transportable once printed and easily re-assembled onsite by a few team members. This house has a $28m^2$ ground level surface, classifying it as a “tiny house”. It also features a mezzanine with sleeping space for four people (Fibonacci House, 2020).

Demonstrated Capability: TAM constructed the Fibonacci house in Canada and is collaborating with World Housing (www.worldhousing.org) to build the first 3D printed village also in Canada (World Housing 2021). One of the major challenges in securing permission to build the Fibonacci house was ensuring code officials that the structure would be safe. Working closely with the Laticrete team, TAM compiled the mechanical properties of the 3D mortar—strengths, freeze-thaw performance, thermal conductivity, and coefficient of thermal expansion. The Regional District of Central Kootenay, B.C., where the Fibonacci house was built, has the capacity to acknowledge engineering calculations as a substitute for known construction conditions. The building officials accepted the use of the Laticrete 3D Printing Mortar as a nonconventional leave-in-place formwork material. This allowed TAM to secure the approvals necessary to erect the house.

16. WASP

Figure 34: Images and Summary of WASP Printer Characteristics

Company Location:	Italy
Date Started:	2012
Website:	https://www.3dwasp.com/
Printer Model:	Crane WASP
Printer Type:	Gantry System
Printer Availability:	For Sale
Indicative Pricing:	> $200,000 USD
Maximum Build Size:	6M diameter, 3m height; modular
Printer Dimensions:	12 m in height and 7 m wide, with adjustable arms that can extend up to 6 meters.
Printer Weight:	150 kg
Power Requirements:	1500 Watts
Printing material:	Non-proprietary
Setup Time:	Less than one day

Company Background: World Advanced Saving Project, or WASP, is an Italian company that developed a concrete 3D printer called the Big Delta, arguably the largest concrete 3D printer currently on the market (WASP, 2021).

Printer Description: WASP uses a delta-style rather than cartesian-style gantry system because it works moving only the extruder. This enables much lower energy consumption and less wear on the mechanical parts. It also enables easier and faster assembly of the gantry printer, which is more than 10 meters in height and is designed to be assembled without using stairways or scaffoldings (WASP, 2021).

Construction Material: WASP can extrude fluid-dense materials of any kind. It has been designed to print concrete (made from local Earth based materials along with concrete mortar and geopolymers), lime-based mixtures, sawdust and polystyrene, as well as materials that are found on location, a mixture of water, soil and vegetable fiber, depending on each territory (WASP, 2021).

Transportability: All components are transported disassembled in a specially designed container. The container, transported on site, offers all the necessary tools to build a self-sufficient village through the most advanced additive technologies. Depending on the territory and the project, one can choose the optimal printing configurations, by assembling each single module in different ways (WASP, 2021).

On-Site Construction Capability: WASP is designed to be able to print on-site using natural mixes, with the addition of natural fibers for architectural-scale construction.

Demonstrated Capability: WASP designed and printed Gaia, an eco-sustainable house, on-site in Massa Lombardo to demonstrate the potential of 3D printing in architecture. WASP's double dome solution makes it possible to construct the foundation, walls and roof in a single monolithic printing. The house was entirely created with reusable and recyclable materials, sourced from local soil, carbon-neutral and adaptable to any climate and context. The double dome solution made it possible to cover at the same time the roles of structure, roof and external cladding, making the house high-performance on all aspects (WASP completes its TECLA 3D printed house, 2021).

17. XtreeE

Figure 35: Images and Summary of XtreeE Printer Characteristics

Company Location:	France
Date Started:	2015
Website:	http://xtreee.com/
Printer Type:	Robotic Arm (developed by ABB)
Printer Availability:	Lease and collaboration
Indicative Pricing:	TBD
Maximum Build Size:	3 m high and 5 m long without being repositioned
Printer Dimensions:	1.5m x 1.5m x 3.0m (Width x Length x Height)
Printer Weight:	1,200 Kg.
Power Requirements:	TBD
Printing material:	Proprietary
Setup Time:	Less than an hour, 1 to 2 people.

Company Background: XTreeE is a French startup that develops advanced large-scale 3D printing technology for architectural design, engineering, and construction. XtreeE is rolling out its network of connected 3D printing units for construction globally. XtreeE has its pilot plant in Paris-Rungis, a new production unit in Dubai operated by Concreative, and is opening two other units in Japan and the United States. XtreeE today offers an integrated design-build solution for large-scale additive manufacturing. In 2021, it plans to initiate its digital platform “XtreeE Printing-as-a-Service”, intended to connect customers to the community of designers (architects, designers and engineers) and to 3D printers. XTreeE is partnered with Vinci – the largest civil engineering firm in the world in terms of revenue and LaFarge - Holcim - one of the largest concrete and building material providers in the world (XtreeE, 2021).

<u>Printer Description</u>: The XtreeE printer uses a six-axis robotic arm from AAB, one of its partners. This machine is capable of a wide range of movement by a combination of its six different rotational joints. The complex joint movements are coordinated through a specific programming software developed by XtreeE.

<u>Construction Material</u>: The construction materials, referred to as Ultra-High Performance Concrete ("UHPC"), were designed by XtreeE's partner, Lafarge Holcim. UHPC has strengths of 150MPa, and can go as high as 250MPa, beating traditional Portland-based concrete up to 6-8 times. The same is true for flexural strengths and tensions strengths, reaching up to 40MPa and 10MPa respectively. Given the presence of steel fibers, it is very ductile, and can withstand repeated stress cycles and deformations. It is also self-compacting, due to the high content of superplasticizers and fines, which also gives a smooth and aesthetically pleasing surface with abrasion resistances comparable with natural rock. It is also resistant to chemicals and damaging environmental factors, cracking, shrinkage, and thermal variations (freeze-thaw cycles), it is impermeable to water, and resists heavy chloride migration inside the concrete, that would consequentially corrode the steel inside. This exceptional concrete comes also with a high price, around 20 times more than traditional concrete.

<u>Demonstrated Capability</u>: XtreeE printed five individual houses in 2020 in Reims, France. The construction was supported by the social landlord Plurial Novillia of the Action Logement group.

<u>Comparison of Key Characteristics of the 3D Printers Reviewed</u>

The following table provides a comparison of key features among the various printers described in this Study. As earlier stated, this information reflects what is available from various public sources during the research phase of this Study, but this is a dynamic and competitive industry, so it may not accurately or completely reflect current status. Nevertheless, the review is as objective as possible.

Figure 36: Comparison of Key Features Among 3D Printers Surveyed

Company:	Printer Type	Availability	Price ($ USD)	Price All Inclusive*	Max-Build Size (m)	Proprietary Concrete Mix	Weight (Kg)	Power (kW)	Workers / Time to Set Up	Remote Support
APIS-COR	Robotic Arm	Sale	$300K+	Yes	8.5 x 1.6x 1.5	Yes	1,814	8	2 / < 1	✓
Batiprint	Robotic Arm	Sale or Lease	$300K+	Yes	4.7m H x No limit W & L	Yes	907	20	2 / < 1	✓
BeMore3D	Gantry	TBD	TBD	Yes	TBD	Yes	800	6	3-4 / 4	✓
BetAbram	Gantry	Sale	$300K+	Yes	2.5 x 8.2 x 16.0	No	500	4	3-4 / 4	✓
Black Buffalo	Gantry	Sale, Lease, Project	$400K+	Yea	13ft x 8ft x H7.2ft	Yes	TBD	TBD	TBD	✓
COBOD	Gantry	Sale	$375K - $1M+	Yes	9.0 x 12.0 x Infinite Length	No	4,500	25	2/ 4-6	✓
Constructions-3D	Robotic Arm	Sale	$550K+	Yes	9.5x 9.5x 3.3	Yes	2,500	7	2/ 4-6	✓
Contour Crafting	Gantry	Lease	TBD	Yes	TBD	Yes	< 1,000	TBD	TBD	✓
CyBe Construction	Robotic Arm	Sale	$260K+	Yes	2.5x 5.0x 4.0	No	3,500	8	2 / < 1	✓
	Gantry	Sale	$180K - $400K+	Yes	TBD	No	TBD	8	3 - 4 / < 1	✓
Hyperion Robotics	Robotic Arm	Sale	$350K+	Yes	5.0x 5.0x 2.0	No	1,450	15	2 / < 1	✓
ICON	Gantry	Sale, Lease, Project	$250K+	Yes	2.6 x 8.5 x Infinite Length	Yes	1,724	16	TBD	✓
MudBots	Gantry	Sale	$175K - $2.4M	Yes	1.83x 1.83x 1.2	No	623	TBD	3-4 / 2	✓
SQ4D	Gantry	Lease	TBD	Yes	9.1 x 4.4 x infinity	No	TBD	TBD	3-4 / 2	✓
Total Kustom Rudenko	Gantry	Sale	$300K - $900K+	Yes	6.0x 10.0 x 20.0	No	2,269	1.6	3-4 / < 1	✓
Twente Additive Mfg.	Gantry	TBD	TBD	Yes	9.0 x 40 x 15.0	Yes	TBD	TBD	3-4 / 4	✓
WASP	Gantry	Sale	$200K+	Yes	TBD	No	150	TBD	3-4 / 4	✓
XtreeE	Robotic Arm	Sale, Lease, Project	TBD	Yes	1.5 x 1.5 x 3.0	Yes	1,240	TBD	2 / < 1	✓

* Price includes printer, pumps, controller, software, training and warranty

Seventeen companies were reviewed between the United States and Europe that have developed 3D concrete printers for the construction of houses and other building structures. Eleven of these companies have chosen to go with gantry-style printers while five have chosen robotic arm-style printers, and one company, CyBe Construction, has chosen to develop both types. Almost all these companies offer their printers for sale or lease, while also using them for housing or building construction projects under contract or in collaboration with 3rd parties. Sales prices for these printers range from $180K US dollars to more than $2M US dollars. In addition to the printer, the price typically includes the pump, controller and software, along with training and a 1-year limited warranty. Nine of these companies also require the purchase of their own proprietary concrete mix for use with their printers, while the other eight allow the use of any mix the purchaser deems appropriate, as long as it is compatible with the printer.

All the printers are ruggedized for onsite printing and built to be highly reliable with very low maintenance and ease of repair. The power requirements for these printers vary from about 2 kilowatts at the low end to more than 25 kilowatts at the high end. The average power requirement for the printers surveyed is approximately 11 kilowatts. The weight of the printers ranges from a low of 150 kilograms for the lightest gantry-style printer, to more than 4,500 kilograms for the heaviest robotic arm printer.

Set-up time for robotic arm-style printers is generally less than one hour, whereas gantry-style printers can take up to six hours to install, and a day to tear down and build back at an adjacent construction site. The robotic arms typically take one to two workers to set up and operate, while the gantry style printers typically require 3-4 people.

Key Considerations for the Selection of a Suitable 3DCP for Rural Alaska

Gantry vs. Robotic Arm: The habitat model designs presented in this Study by PSU are based on using a Robotic Arm printing system, as opposed to Gantry Frame system. PSU's view is that while the latter can also be used, it is less flexible and limited to 3-axes, more difficult to transport and set up especially in rural and remote areas that are hard to reach and / or have difficult terrain. PSU's robotic arm printing system has 6 axes of freedom, and according to PSU is more agile, more compact, easier to alter and adapt, easy to deploy (folded in transit), easy to assemble, can perform multiple tasks (using tool-changing mechanism), can achieve more complex geometries, can be equipped with compound extensions for arm's reach, and can be attached to a mobile base for additional flexibility on-site or ease of movement between sites (Penn State Report 2021).

According to PSU, the flexibility of the 6-axis Robotic Arms systems would enable the entire structure to be printed monolithically, on-site, including an integrated roof and enclosure, whereas the gantry frame system, in the current state of the technology, is capable of printing mainly vertical walls (Penn State Report 2021).

Transportability: Transportability is a function of weight, transport dimensions and ease of setup in remote areas without the need for heavy lift or support equipment. The printers surveyed ranged in weight from 150 Kg. to 4,500 Kg., with both gantry and robotic arm-style printers spanning the range. Weight affects transportability of the printer and associated equipment to the remote site in Alaska from the printer's point of origin. Transportation options may include truck, air cargo, cargo ship or barge, depending on the origin, destination, weight, and dimensions of the equipment. From the lower 48, it is possible to transport the equipment by truck to destinations on the main Alaska road system as far north as Deadhorse. Other destinations, such as Nome, with no connecting road system but air and seaport capabilities, can support delivery by air cargo, cargo ship or barge. More inland locations, such as Bethel or Chuathbaluk, will be further limited, depending on local infrastructure, e.g., availability and condition of local roads (which are often gravel or dirt), size of local airport runway, or, if water access is possible, river barge. Weight is generally not a factor with trucks traveling major roads, but it is a factor in the bush where roads are often gravel and dirt, and not designed for heavy trucks and equipment. Weight is also not a factor with ships or barges, or where local airport runways can support large planes such as a Boeing 737, Swingtail, Lockheed C-130 or the like, but is a factor where local runways are too small to support the larger planes (Alaska Air Cargo, 2021; Alaska Air Forwarding; 2021, Lynden Air Cargo, 2021).

While the size of the various printers surveyed should not be a limiting factor on trucks, ships and barges, size matters where air transport is required: The C-130 cargo dimensions are 664" (L) x 120" (W) x 120" (H). Boeing 737 air cargo typically has a limit of 120"(L) x 80" (W) x 73" (H). Smaller planes have lower limits (Lynden Air Cargo, 2021; Alaska Air Forwarding, 2021; Alaska Air Cargo, 2021). This will be an important consideration when selecting a printer, depending on the range of destinations in rural Alaska for its intended use.

Build Size: Once the printers are set up, gantry type are more stable than robot arm printers, and depending on the size of the gantry, can print larger building structures without having to move the gantry. Build size for robotic arms is limited by the extension and its degrees of freedom of movement, and its ability to move from one printing position to another at the construction site. The gantry frame must be larger than the structure to be built, which can require a massive system along with costly transportation, setup and teardown processes.

Setup and Mobility: Robotic arm-style printers typically have a more compact form factor than gantry-style printers and can be installed on a motorized mobile platform with tank tracks, making them easier to set up, transport and move around the construction site in less-than-ideal terrain. While some gantry-style printers are designed for setup by several people without the need for support equipment, the larger systems may require a crane for setup and teardown; this will be difficult and expensive in many parts of rural and remote Alaska. Gantry-style printers also require anchors in the ground for the gantry structure, or level rails on top of an existing concrete foundation to function properly; this may be difficult to achieve where terrain at the building site in rural Alaska is rough or uneven. Similarly, for robotic arms that are not attached to a mobile platform, a forklift or crane may be required to assist in the setup and any movement of the equipment around the construction site.

Power Requirements: The power requirements for the 3D printers vary greatly depending on individual printer design, from about 2 kilowatts at the low end to more than 25 kilowatts at the high end. The average power requirement for all 17 printers surveyed in the Study is approximately 11 kilowatts. If local power is not available, power sources could include portable generators running on diesel, propane or hybrid fuels. A solar / battery system might also be a good power source since ample sunlight is available coincident with the build season and the homes will need a power source once they are completed. Wind power might also be an option.

Concrete Mix: Of the 17 printer companies and their products described in this Study, nine require the use of proprietary concrete mixes for use with their printers, and eight do not. However, most of the companies, whether requiring use of their mix or not, allow for the incorporation of local geologic materials into the mix (e.g., sand, gravel, shells or other suitable material from sources near the construction site), without voiding the warranty. The extent to which local materials can be sourced and converted to printable concrete mix at the site will reduce the need to transport such materials to the site and hence further reduce the cost of construction.

Reliability: All of the printers appear to be of rugged, industrial strength construction and operating capability. The printing companies all represent that these machines are ruggedly built to function in adverse outdoor conditions while at the construction site, with low maintenance, spare parts on-site, ease of part repair or replacement, and real-time virtual technical and operational support. However, any kind of construction with concrete – conventional or 3D concrete printing – will need some level of protection during the setting and curing process from extreme cold, heavy precipitation (rain or snow), heavy wind or dust. One approach to mitigating these conditions has been the use of a sturdy waterproof, windproof, heated tent over the construction site.

Remote Support: All of the printer companies reviewed offer “real-time” remote technical and operational support. Further research is required to determine if this is 24/7 or limited to certain time zones. It will be critical to ensure that such real-time support is available during Alaska summer operations– in order to take full advantage of extended daylight hours in Alaska during the build season.

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TASK 3: ENGINEERING ANALYSIS OF CONCRETE 3D PRINTED STRUCTURE

Pennsylvania State University's Additive Construction Laboratory ("AddConLabs") was contracted to research and analyze structural designs appropriate for the permafrost regions of rural Alaska and concrete 3D printing. PSU and AddConLabs have extensive experience and expertise with architectural and engineering design with 3DCP structures as well as advising NASA on 3DCP printed habitats. PSU faculty and graduate students successfully competed in and won 2nd place in the NASA Challenge for 3DCP habitats using remote control to build a prototype habitat in 30 hours. PSU owns and operates its own concrete 3D printer and related software and equipment. The PSU team includes Ph.D. level architects, structural engineers, and civil engineers with expertise in concrete assisted by graduate students of architectural engineering.

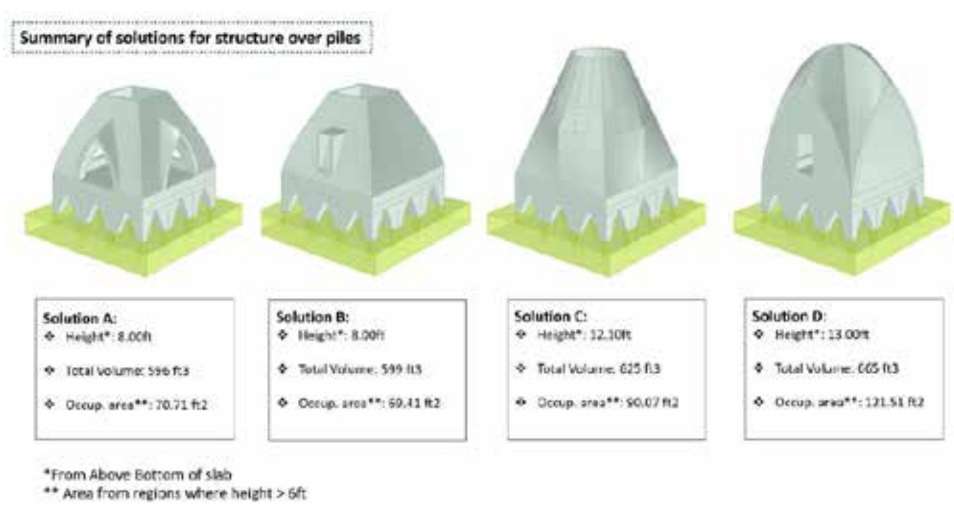
For the purpose of this Feasibility Study, design parameters for a small prototype building were established from peer-reviewed research of general Alaska local architecture, international design concepts, and U.S. government agencies 3D concrete printed structure concepts for unique or extreme environments. The Abstract of PSU's Design and Engineering Analysis, attached as Appendix A to this Study, is as follows:

> The objective of this project is to explore the feasibility of 3D printing concrete homes in Alaska for permafrost regions. The project is developing conceptual design schemes for a small building with approximate dimensions of 12 ft x 12 ft x 10 ft, with shape and configuration suitable for 3D printing of the entire structure. The feasibility study considers both applicable loads on the structure (self-weight, snow, wind, earthquake) and thermal aspects of the structure and foundation.
>
> It is of primary concern to avoid heat transfer between the structure and the supporting ground, and this drives the configuration of the design, which foresees the creating of a crawlspace to allow air circulation between the top of ground and the underside of the structure. While this is the preferred solution at this point, the study is also looking into the option of having a slab on grade design, such that crushed rocks and insulation assist in avoiding the transfer of heat to the permafrost. For the elevated design with the crawlspace feature, it is assumed that the printed concrete column will be located on top of wooden or steel piles that extend through the active layer and into the permafrost zone.

> The project also includes developing material test results, such as compressive strength and modulus of rupture, based on the concrete cylinders provided to us. As the project evolves, we intend to address cultural values and maintain high standards regarding architectural design and the aesthetics of the 3D-printed structures, while considering local building regulations and materials, technical issues related to additive construction, engineering of the structural and environmental systems, and proper insulation and finishes.

While there is no substitute for a detailed review of the complete PSU Design and Engineering Analysis, the following conclusions have been extracted from that Analysis (pages 88 and 89) for the benefit of the broader Feasibility Study:

> When it comes to 3D printing, one should note that in digital design and Robotic Additive Construction, it does not make any difference to design and/or print straight or curved walls. Furthermore, the advantage of 3D printing is that is can be custom made, yet mass produced, resulting in mass customization, which means, we have a construction system that can produce custom made buildings without added cost. Considering the facts that we would be building in extreme weather conditions with heavy snow and storms, and using 3D Printing technologies, domed and vault type structure are determined to be ideal.
>
> Four different habitat forms were developed for slab on grade and elevated options, but two of them were more suitable for detailed analysis (Models B and D).



Between the two, Model D with the closed roof is the preferred concept as it can be fully printed without the need for a different roof material or system. Architectural design considered different printing options for walls, such as single wall and double walls, the needed insulation type, position, and finish materials. The foundation systems considered both a piled system extending in the permafrost zone and slab on grade. Both systems provide for appropriate thermal break to avoid heat transfer to the ground, in particular, permafrost layer.

The habitat system that is elevated above ground is a more complex structure, as it includes a slurry displacement pile, adjustable jacks on top of piles to compensate any potential settlement due to heaving, printed columns on top of adjustable jacks, arch type structure support, slanting walls closing at roof with the option of having a slab or glass skylight at the top or completely monolithically closed top, which provides a jointless structure. For structural evaluation, deadload, snow load, wind load and seismic effects were considered and these elements determined some of the dimensions for vaulted columns beneath the floor slab, and for the rebars inside them.

Below is a summary of the main outcomes from the study:

a) Presentation of a review of typical residential construction requirements in Alaska permafrost regions

b) Determination of the parameters and factors to consider in design of a habitat for rural regions.

c) Development of strategies for how to consider constraints and requirements for constructing a habitat based on the 3D printing technology.

d) Study of various foundation options and choosing a slurry displacement pile system for piled foundation to support elevated structure, and a slab on grade foundation without excavation (solidly raised above undisturbed ground on bed of sand and gravel).

e) The piles can be wooden or tubular steel, but the preference would be wooden piles.

f) Development of finite element modeling and analysis for two of the four designed habitat models and performing structural analysis considering applicable load combinations for dead, snow, wind, and seismic loads. Based on the results of the analysis, we refined the design parameters for the columns, including dimension and reinforcement requirements.

g) Review and narrowing down the type of pile system to use.

h) Development of a design detail for adjustable jack at the connection between the pile top and the supporting column for the case of elevated habitat option to include jacking option for settlement adjustment.

i) Specification of the option of spray foam insulation for the habitat interior to minimize heat transfer from the building to the ground.

j) Specification of the option of polyurea as the finish material for the exterior and interior of the Specification of the XPS insulation type/thickness and preliminary details of the sand and gravel beds for the foundation under slab on grade.

k) Carrying out tests on received concrete cylinder samples and providing an analysis of the results, which shows significantly lower compressive capacity compared to what is needed to provide the capacities of the structural components.

l) Suggestions for improving the sample preparation to obtain more improved compression capacities.

m) Configuration of printing machine setup and toolpath requirement for field printing.

In Summary, based on this Phase 1 study, it is concluded that the developed schematic designs can work safely under all applicable loading types that were considered. The results show that 3D printing of a habitat of the size and configuration studied is feasible. Applicable and relevant parameters for design, construction, and operation of 3D printing system in remote Alaska areas have been identified and either quantitatively specified or suggested for further follow-up Phase 2 detailed study.

TASK 4: MATERIALS ANALYSIS RE: SELECTION AND USE OF GEOLOGIC MATERIAL IN DIFFERENT ALASKAN REGIONS FOR 3D CONSTRUCTION

Task 4 Study analyzes geologic samples from three diverse regions in Alaska to determine its viability as material for 3DCP. PSU's AddConLabs was contracted to conduct concrete pressure tests of Alaska-based sample ingredients from Alaska sites mixed with Portland Cement to form concrete samples.

On March 9, 2021 XHI received Alaska samples from Anchorage, Fairbanks and Juneau. Each sample included a mixture of rocks <5 inches diameter, gravel, and sand size particles <9mm in diameter.

Figure 37: Alaska Site Samples

Sample From Anchorage	Sample From Fairbanks	Sample From Juneau
		

Preparation of concrete samples included acquiring PVC concrete sample test form cylinders, Portland Cement, water, contractor sand, and portable rock crushing equipment. Portland Cement was selected to make concrete samples instead of Quikrete due to the fact that Quikrete has many different types of ready-mix concrete with different binding ingredients. Some Quikrete types may not be appropriate or not available in Alaska. Consequently, generic Portland Cement available in Alaska was used.

Upon receipt of the sample materials, materials were crushed with a portable rock crusher, washed and filtered to obtain a particle size of less than 4mm. This particle size is a correct size to use in a concrete 3D printer to form a structure. Some manufacturers of concrete 3D printers state its equipment can use up to 9mm size particles, but that large size causes faster wear of the equipment. Unfortunately, the samples were not properly mixed by a third party, back-up samples had to be tested. These samples were shipped in raw form to PSU for proper mixing and testing. Following ASTM protocol, the samples were prepared and cured for 28 days. The results were positive with each sample achieving a compressive strength of more than 6,000psi. Appendix B contains the detailed results of the re-test.

Previous engineering tests of 3D printed concrete reveal 3D printed concrete is as strong or stronger than cast concrete (Briggs 2019 & Murcia et.al. 2020). Following are other engineering test results for 3D printed concrete and cast concrete samples. The tests were conducted for a manufacturer of concrete 3D printer equipment.

Figure 38: 3D Printed Concrete Test

Briggs Engineering & Testing
A Division of PK Associates, Inc.

October 30, 2019

Apis Cor Engineering LLC
2 Bowdoin Street
Apt. 324
Everett, MA 02149

Briggs #30851

Attn: Nikita Cheiuntai

EVALUATION OF CONCRETE MASONRY UNITS
Apis Cor-Lab Testing

DATE RECEIVED: July 15, 2019

SPECIMEN: Two 3D printed blocks made by the the above referenced project and delivered to our Rockland facility for testing.

METHOD OF ANALYSIS: Sampling and Testing Concrete Masonry Units ASTM C 1314.

RESULTS

Specimen#	Age at Test (days)	Gross Area, in^2	Net Strength,psi	Max Load, in.	Corrected Strength,psi
A (Hollow)	112	85.73	2060	176330	1520
B (Grouted)	112	88.94	3010	267790	2230
		AVG.	2540	AVG.	1880

Respectfully submitted,

BRIGGS ENGINEERING & TESTING
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Figure 39 Non 3D Printed Concrete Test

Briggs Engineering & Testing
A Division of PK Associates, Inc.

October 30, 2019

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Everett, MA 02149

Briggs #30851

Attn: Nikita Cheiuntai

EVALUATION OF CONCRETE MASONRY UNITS
Apis Cor-Lab Testing

DATE RECEIVED: September 17, 2019

SPECIMEN: Two 8"x8"16" C.M.U. samples made by the the above referenced project and delivered to our Rockland facility for testing.

METHOD OF ANALYSIS: Sampling and Testing Concrete Masonry Units ASTM C 1314.

RESULTS

Specimen#	Age at Test (days)	Gross Area, in^2	Net Strength,psi	Max Load, in.	Corrected Strength,psi
A (Hollow)	36	69.86	1740	121530	1260
B (Grouted)	36	119.14	3690	439350	2660
		AVG.	2720	AVG.	1960

REMARKS

Respectfully submitted,

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Task 4 End Notes

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TASK 5: COST / BENEFIT COMPARISON ANALYSIS OF 3D PRINTED HOUSING VS. CONVENTIONAL CONSTRUCTION FOR RURAL ALASKA.

This Task provides a Cost / Benefit Comparison ("CBC") of 3DCP vs. conventional construction in rural Alaska. The purpose of the comparison is to introduce various costs and risks as well as anticipated benefits and opportunities as a means of determining if the benefits of 3DCP outweigh the costs. This CBC is the first step in a process to determine if 3DCP is a viable option compared to conventional construction of affordable housing in rural Alaska. The next step will be to build a prototype to determine the effective and actual cost. The third step will be to consider the use of 3DCP for affordable housing, if steps 1 and 2 yield positive outcomes.

Benefits of 3DCP VS Conventional Construction Methods

The use of 3DCP is believed to offer solutions to the construction of more affordable housing in Alaska, particularly for remote, isolated communities having limited construction infrastructure. Alaska's rural remote communities are characterized by geographic isolation, extreme weather conditions, underdeveloped economies, and risks and hazards associated with the construction supply chain.

For 3DCP to be considered a viable construction alternative it must be competitive with conventional construction as well as proven useful in addressing Alaska's particular construction challenges. Substantiation of benefits and costs is achieved through research findings, including a direct comparison of the cost to construct a prototype housing structure in rural Alaska using 3DCP, versus the cost to construct the same structure using conventional construction methods.

Since the beginnings of 3DCP technology in the 1990's, peer-reviewed scientific research has clarified the benefits of 3DCP structures over conventional construction methods. Benefits include the following: reduced construction time, labor savings, lower materials costs, possible use of local materials for construction, improved labor safety, increased design opportunities, less waste, scalability and reduced environmental impact. These benefits are highlighted in Figure 40 below.

Figure 40: 3DCP Benefits vs Conventional Construction

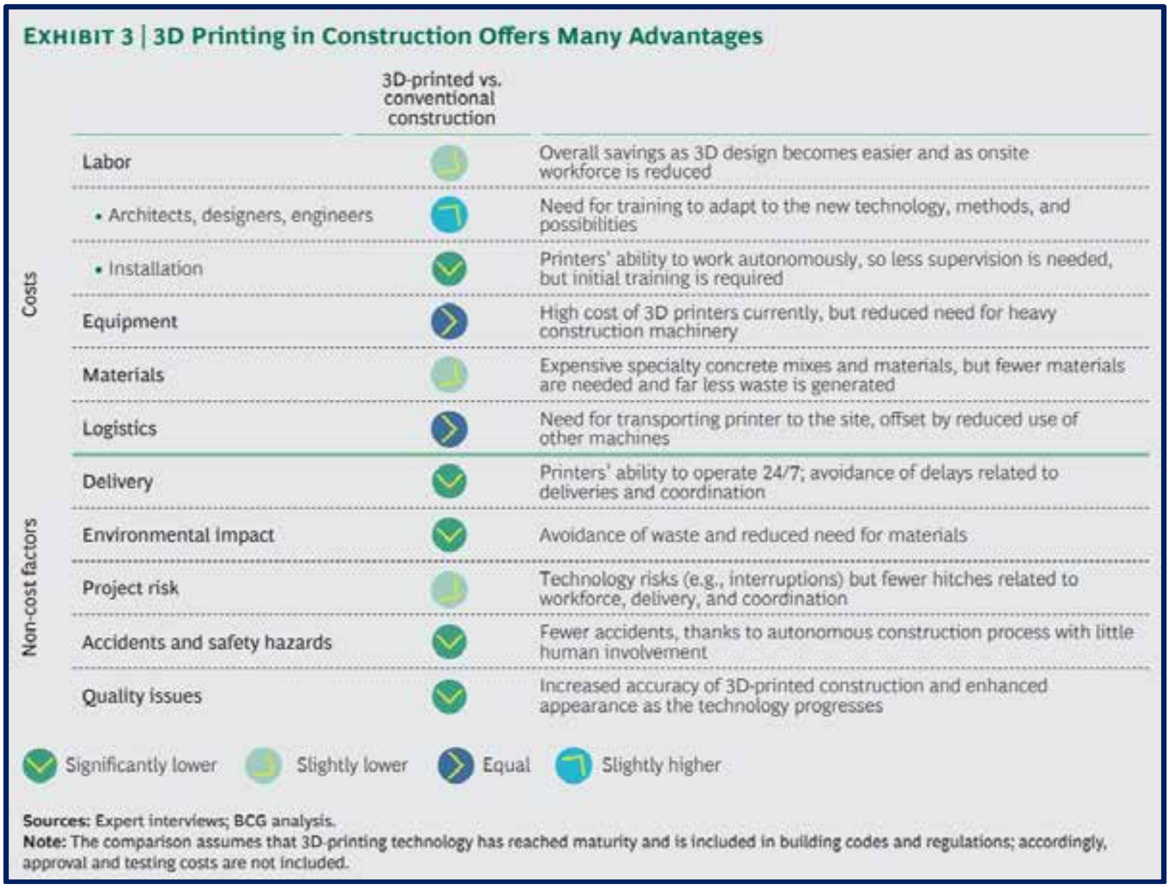


EXHIBIT 3 | 3D Printing in Construction Offers Many Advantages

		3D-printed vs. conventional construction	
Costs	Labor	Slightly lower	Overall savings as 3D design becomes easier and as onsite workforce is reduced
	• Architects, designers, engineers	Slightly higher	Need for training to adapt to the new technology, methods, and possibilities
	• Installation	Significantly lower	Printers' ability to work autonomously, so less supervision is needed, but initial training is required
	Equipment	Equal	High cost of 3D printers currently, but reduced need for heavy construction machinery
	Materials	Slightly lower	Expensive specialty concrete mixes and materials, but fewer materials are needed and far less waste is generated
	Logistics	Equal	Need for transporting printer to the site, offset by reduced use of other machines
Non-cost factors	Delivery	Significantly lower	Printers' ability to operate 24/7; avoidance of delays related to deliveries and coordination
	Environmental impact	Significantly lower	Avoidance of waste and reduced need for materials
	Project risk	Slightly lower	Technology risks (e.g., interruptions) but fewer hitches related to workforce, delivery, and coordination
	Accidents and safety hazards	Significantly lower	Fewer accidents, thanks to autonomous construction process with little human involvement
	Quality issues	Significantly lower	Increased accuracy of 3D-printed construction and enhanced appearance as the technology progresses

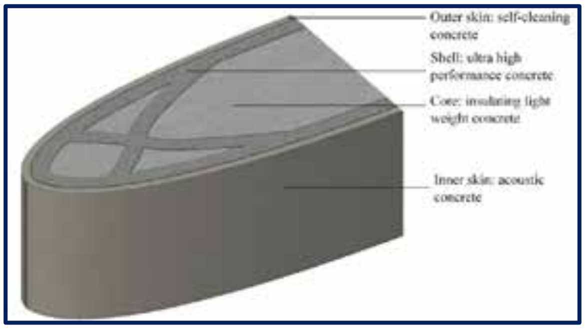
Significantly lower · Slightly lower · Equal · Slightly higher

Sources: Expert interviews; BCG analysis.
Note: The comparison assumes that 3D-printing technology has reached maturity and is included in building codes and regulations; accordingly, approval and testing costs are not included.

From: The Boston Consulting Group 2018, p.13

Furthermore, because the resulting housing structures are concrete, 3DCP has benefits over conventional construction for longevity, structural integrity, seismic resilience, and strength against extreme weather (snow loads, 200mph strong winds, etc.) or human incidents (vehicles crashing into structure, 7.62 caliber rifle shots, etc.). Additionally, some studies indicate that 3DCP wall patterns may afford similar benefits as conventional construction related to thermal insulation. The wall pattern shown in Figure 41 below is indicative.

Figure 41: 3DCP Insulation Pattern



From: Bos et.al. 2016, p.210

Reduced construction time results from not having to use concrete form molds, eliminating the time required to frame a house, the speed of 3DCP, and reduced labor per house. This reduction in construction time translates into lower costs compared to conventional construction. Whereas conventional construction of just the external framing of a house typically takes two to three months depending on weather and availability of labor, 3DCP construction of the external "shell" of a house (foundation, walls and roof) typically takes one to three days depending on weather.

Also, by eliminating forms and framing from the construction process, a significant hazard is removed, resulting in the likelihood of less injuries. Reduction of waste is another significant factor. Forms are typically not used more than once and framing requires custom cuts of lumber, all of which results in large amounts of wasted materials.

Another potential source of cost savings could be the use of local geologic resources as aggregate in the concrete mixture for 3DCP. Alaska's numerous and geographically distributed outcroppings of sand, gravel and rock could be inexpensive sources of materials to substitute for some of the ingredients that would otherwise need to be imported for the concrete mixture. Extraction of such materials will most likely require government permits (e.g., from the Alaska Department of Fish and Game, the Alaska Department of Natural Resources and agencies of local zoning districts, etc.). Quarries in Alaska with existing government permits for resource extraction can be found at the following website: www.dot.state.ak.us/stwddes/desmaterials/matsiteportal/materialsitemap.cfm.

Figure 42: Juneau Site of Test Sample March 2021

Local Geologic Material That Could Be Used for 3DCP

As previously described, 3DCP is driven by Computer Aided Design or CAD and Building Information Modeling or BIM software that also speeds up construction. Instead of printing out hard copies of architectural plans for various trade workers to use to construct a building, this time and effort is skipped with 3DCP. The CAD and BIM data is transmitted directly to the robot for construction. “Digital fabrication techniques can increase productivity rates in the building industry not only because they lead to significant time saving for complex designs, but also because they exhibit the ability to transfer design data directly to 1:1 assembly operations and automated construction” (Garcia de Soto 2018, p. 298).

With concrete 3D printed houses there is a time trade off with costs that favors 3D printing over the long-term or a large quantity of production. A concrete 3D printer is expensive equipment and not cost effective to build one small structure compared to the paid labor hours for conventional construction of a small structure. However, a 3D printer may have a life of five to ten years (45,000 to 90,000 hours) and when used over time its costs reduce relative to conventional construction paid labor hours. The cost of the 3D printer is amortized over time or the amount of concrete used, while conventional construction labor costs rise over time. According to Garcia de Soto et.al. (2018) analysis of 1,000 iterations of conventional and robot printed walls, the more concrete used and more complex the structure result in larger cost savings using 3DCP. In summary, the cost of 3DCP of a house decreases with additional houses constructed, while in conventional construction the cost stays the same or increases with each additional house built.

Another potential benefit of 3DCP is its potential to significantly decrease the number of injuries and deaths in the construction industry by eliminating many of the dangerous and laborious tasks of manufacturing a building. Traditional construction methods tend to be unsafe and lead to worker injury. According to the United States Bureau of Labor Statistics, 4 out of 100 full-time American workers in 2010 were injured or contracted a work-related illness, and 802 total annual American fatalities were reported. This is the largest number of deaths in any sector, making construction one of the most dangerous professions in the country." (Keating, 2014, p.386). In Alaska's case, after the Fishing industrial sector that is uniquely extensive to Alaska, construction of buildings has the highest death rate for an industrial sector: 0.07 % of construction building workers (Alaska Department of Labor and Workforce Development 2019 and U.S. Bureau of Labor Statistics 2019).

Holistically, there are several different benefits of 3DCP compared to conventional construction, and there are several different cost savings compared to conventional construction methods. In addition to the less cost per square foot of 3DCP presented in the following section, the broader range of benefits and less costs are described in the following Figure. Some benefits and cost savings are not stated but can be significant to a construction firm. For example, with less injuries using 3DCP compared to conventional construction, Worker Compensation Insurance rates and fees are less.

Figure 43: 3DCP Internal Strengths and Weaknesses and External Opportunities and Threats

Internal factors	
Strengths (S)	Weaknesses (W)
❑ Reducing construction time ❑ Increased precision ❑ Reduces construction waste ❑ Minimises transportation cost ❑ Allows for complex geometries realisation. ❑ Better control of the construction process	❑ High capital cost & expertise needed ❑ Technical problems; applying reinforcement, control of print path, height and speed as well as the rate of extrusion. ❑ Design parameters; apparatus design and operating system ❑ Material content: flowability, buildability, extrudability, stiffness and strength.
External factors	
Opportunities (O)	Threats (T)
❑ Applying BIM integrated technologies ❑ Integrating latest scientific findings with industrial practices ❑ Competitive advantage of 3DP and the real estate market acceptance and future development including clients and customers	❑ Socioeconomic consideration: reducing job opportunities ❑ The need for special building codes that suit the use of the technology ❑ Less incentives and awareness

From: Geneidy, et.al. 2019

Conventional Construction vs 3DCP Construction Cost Per Square Foot Comparison

To clarify the methodology used consistently in construction cost benefit analysis over the past 30 years, the following example by Najafi, et. al., for 3DCP cost benefit analysis is presented in Figure 44 below. While the technology for 3DCP has evolved dramatically since this methodology was first introduced, the same methodology is used today in peer-reviewed scientific research to estimate the cost comparison between 3DCP and conventional construction. See, for example, the research conducted by: Khan et al., 2021; Khajavi et al., 2021; Han et al., 2021; Mahadevan et al., 2020; Arukala et al., 2020; Otto et al, 2020; Valente et al., 2019; Shatornaya et al., 2017; and Robert Bogue, 2017.

Figure 44: Cost Benefit Comparison
Conventional vs Robot Printed Concrete Per Linear Foot

Costs Using Conventional, Non-Robotic Method	
From Means Construction Cost and Data (1991) we can find the standard costs:	
Crew:	2 Carpenters
Wage:	$21.60 / hr.
Output:	5 L.F. / hr.
Material Cost:	$30 / L.F.
Equipment Cost:	$0 / L.F.
Total Unit Cost:	$38.65 / L.F.
Costs Using the Robotic Approach:	
Robot is taken as one kind of equipment:	
Robot Name:	Walbots (developed by MIT)
Investment Cost:	$40,000
Maintenance:	$20,000 / year
Interest Rate:	10%
Useful Life:	5 years
Annual Work Hours:	800 hr / year
Output:	20 L.F. / hr
Crew:	2 workers
Wage:	$17.5 / hr.
Material Cost:	$30 / L.F.
Assumed Salvage Value:	0
Capital Cost:	Depreciation cost + investment cost = $13 / hr.
Operating Cost:	Maintenance cost + power cost + labor wage = $61 / hr.
Total Unit Cost:	$33.7 / L.F.
Comparing the total unit costs of robotic and nonrobotic alternatives we find that the robotic approach is more economic.	

From: Najafi, F.T. and X. Fu 1992

This methodology clarifies important cost categories. “When considering cost, the input can be the total cost (i.e., labor, material, and equipment costs) related to a given installed quantity. In these cases, it is more intuitive to use the inverse of output/input, to determine how much cost a fixed unit of installed quantity (e.g., USD/m2), so that a lower USD/m2 indicates an improved productivity.” (Garcia de Soto 2018, p. 299; See also Mehdi Shahparvari, 2019, p. 51).

Conventional construction cost estimates come from RS Means Residential Cost survey done in 2020 and published in 2021 with data for the Fairbanks Alaska region. For 70+ years RS Means has surveyed all contracting firms' construction projects collecting data on 92,000 line items. In the construction industry including banks financing construction, RS Means is considered the most reliable source of detailed construction costs. RS Means data is collected and available by specific market areas. It is possible for a particular firm to have different anecdotal cost data based on the firm's efficiency and operations unique to it.

Fairbanks was selected because it was the Alaska most remote site with RS Means data. It should be noted however, that the use of Fairbanks for the cost comparison is conservative, since the costs of conventional construction in some rural areas of the State are typically much higher than Fairbanks. The following Table in Figure 45, based on data collected by the Alaska Department of Labor and Workforce Development, Research and Analysis Section, in 2015 for the Alaska Housing Finance Corporation, highlights this difference. While similar surveys have not been published for subsequent years, these cost differences have remained, and in some cases have increased over time.

Figure 45 Difference in Construction Costs: Fairbanks Vs. Rural Areas

Urban / Rural Areas:	% Increase (Over) Fairbanks for Construction Materials*	% Increase (Over) Fairbanks for 2x6 #14 lumber Kiln-dried
Fairbanks	0.0%	0.0%
Anchorage	-13.2%	-12.2%
Juneau	2.9%	16.9%
Kenai	7.6%	11.5%
Ketchikan	8.3%	26.6%
Kodiak	14.3%	34.4%
Sitka	-2.7%	28.4%
Wasilla	2.3%	8.3%
Barrow	128.1%	160.4%
Bethel	84.9%	135.4%
Nome	71.3%	100.1%

*Represents a "Market Basket" of construction materials (without concrete, rebar, doors or windows)

Market Basket consists of: BCI 60 Series 768 ft 14"; 2-4-1 T&G FF Underlay 4' x 8' 62 pcs 1 1/8"; T-111 8" Center Groove 4' x 10' Siding 60 pcs 5/8"; CDX 4' x 8' #53 106 pcs 5/8"; Studs #2 & btr Kiln-dried 164 pcs 2" x 4" 92 5/8"; Studs #2 & btr #14 Kiln-dried 263 pcs 2" x 6" 92 5/8"; 4' x 12' Plain Sheetrock #84 95 pcs 1/2"; 4' x 12' Type X Sheetrock #109 68 pcs 5/8"; Fiberglass Bat Insulation (2,560 sq ft) 40 bags R-38" x 24" 64 sq ft; Fiberglass Bat Insulation (2,034 sq ft) 30 bags R-21" x 15" 68 sq ft; NMB Electric ; Wire 3 boxes 250'; Single Breaker 15 pcs 15 Amp; Copper Pipe Type 'M' 150 ft 3/4"; ABS Pipe 100 ft 3"; 3 Tab Shingles Brown 102 bundles; Metal Roofi ng 3,215 sq ft 3' x 20'.

Source: Alaska Department of Labor and Workforce Development
2015 Construction Cost Survey for the Alaska Housing and Finance Corporation

The cost comparison between 3DCP and conventional construction is based on a 1200 square foot (sf) housing structure with no interior improvements. It consists of a supporting foundation, perimeter walls and roof. There should be little difference of interior costs for a conventional house or a 3DCP house. The cost includes all sub-costs including transport of materials to Alaska.

The cost comparison does not include the costs of rental or transportation of equipment or site preparation (site clear of trees and level flat for construction), because it is identical for both 3DCP and conventional construction, including perimeter walls and roofs. In the conventional construction cost estimate a basic interior wall is included to finish the exterior wall to the inside to be comparable to the finished 3DCP wall so there are no exposed studs. The 3DCP printed perimeter wall is both an exterior and interior wall, and the roof is both exterior and interior as well. Except for the 3D printer cost and shipping that are accounted for in the 3D Printer line-item unit cost shown in 3DCP cost Figure below, all equipment used is the same in 3DCP or conventional construction. As with other engineering cost studies, the comparison is based on cost per square foot including material and labor costs.

Figure 46: Fairbanks Alaska Conventional Construction Cost Per Square Foot

Square Foot Cost Estimate Report

Date: 6/3/2021

Estimate Name	**XHI Prototype Conventional Construction Cost**
	AHFC 1731 South Chandalar Drive Fairbanks Alaska 99775
Building Type	Economy 1 Story with Wood Siding - Wood Frame
Location	FAIRBANKS, AK
Stories Count (L.F.)	1.00
Stories Height	8.00
Floor Area (S.F.)	1,200.00
LaborType	RES
Basement	No
Data Release	Year 2021 Quarter 1
Cost Per Square Foot	$51.38
Total Building Cost	**$61,656.87**

Costs are derived from a building model with basic components. Scope differences and market conditions can cause costs to vary significantly.

		% of Total	Cost Per SF	Cost
01 Site Work		**5.1%**	**$2.62**	**$3,138.49**
	Footing excavation, building, 26' x 46', 4' deep		$2.62	$3,138.49
02 Foundation		**25.6%**	**$13.17**	**$15,798.04**
	Footing systems, 10" thick by 20" wide footing		$3.10	$3,719.54
	Block wall systems, 8" wall, grouted, full height		$10.07	$12,078.50
03 Framing		**26.4%**	**$13.58**	**$16,298.30**
	Exterior wall framing systems, 2" x 4", 16" OC		$0.55	$658.23

RSMeans data from GORDIAN

1

		% of Total	Cost Per SF	Cost
	Truss roof framing systems, 24" OC, 4/12 pitch, 1' overhang, 26' span		$9.59	$11,506.21
	Partition framing systems, 2" x 4", 16" OC		$3.44	$4,133.86
04 Exterior Walls		9.0%	$4.62	$5,548.25
	Wood siding systems, 1/2" x 8" beveled cedar siding, "A" grade		$1.15	$1,384.92
	Non-rigid insul, batts, fbgls, kraft faced, 3-1/2" thick, R13, 15" W		$0.81	$966.69
	Door systems, solid core birch, flush, 3' x 6'-8"		$2.66	$3,196.64
05 Roofing		11.5%	$5.88	$7,058.96
	Gable end roofing, asphalt, roof shingles, class A		$5.88	$7,058.96
06 Interiors		22.4%	$11.51	$13,814.83
	Wall system, 1/2" drywall, taped & finished		$8.35	$10,014.09
	Underlayment plywood, 1/2" thick		$3.17	$3,800.74
Sub Total		100%	$51.38	$61,656.87
Contractor's Overhead & Profit		0.0 %	$0.00	$0.00
Architectural Fees		0.0 %	$0.00	$0.00
User Fees		0.0 %	$0.00	$0.00
Total Building Cost			$51.38	$61,656.87

RSMeans data from GORDIAN 2

Note that the costs for conventional construction shown above do not reflect the more than 200% increase in the price of lumber throughout the US, including Alaska, over the past year, as a result of the corona virus pandemic (Anchorage Daily News, 30 April 2021). Without taking the higher lumber costs into account, the RS Means estimated cost per square foot for conventional construction is $51.38. Note further that this estimate is based on the cost of materials, labor and transportation in Fairbanks, which is a relatively large population center and on the main road system. As shown in Figure 45 above, the cost of the same market basket of construction materials in rural areas around the State, such as Nome, Bethel and Barrow, is significantly higher.

The following 3DCP cost estimate includes exterior walls that are also perimeter interior walls, roof and pilings to prevent heat transfer to permafrost as presented in the PSU Design and Engineering Analysis attached as Appendix A to this Study. PSU faculty provided estimates of required concrete cubic yards based on the design and their experience of having made 3DCP structures with their 3D concrete printer.

Note that while some manufacturers of 3D concrete printers state the machine can have a life of up to 90,000 hours or 3,750 24-hour days (10 years), for the purposes of this Study, a more conservative estimate of 43,800 hours is used or 1,825 24-hour days (5 years).

Figure 47: Alaska 3DCP Prototype Model House Cost Per Square Foot

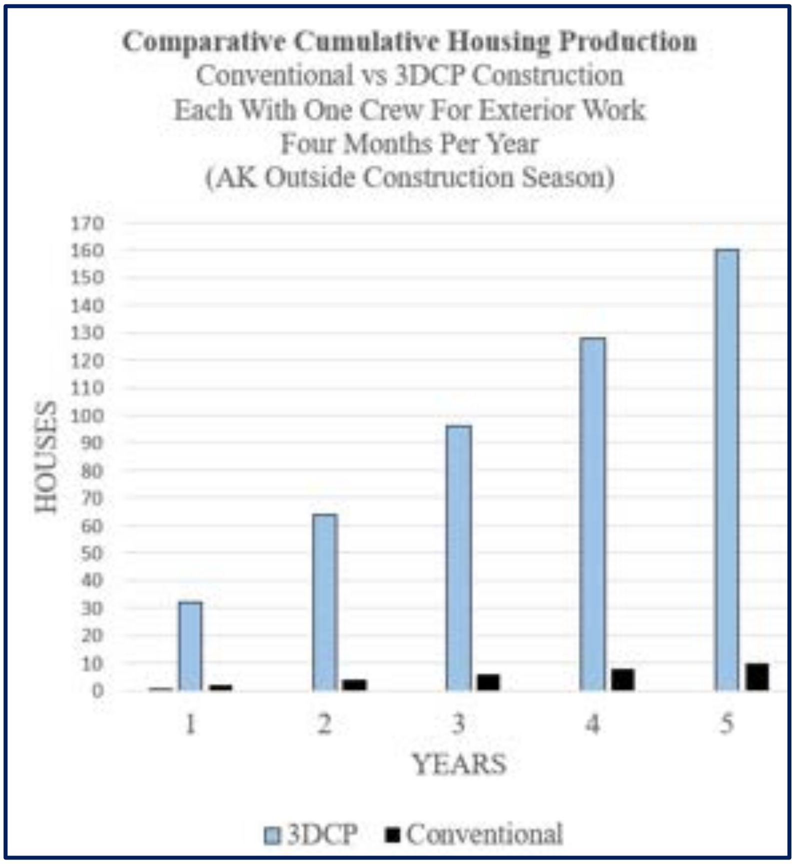
XHI 3DCP Structure Cost (1)		
Structure Square Feet		1200
Alaska Concrete Cost		
Required Concrete (cubic yards)		195.88
Fairbanks Alaska Price / 94 pound Portland Cement bag (1 cubic yard) (2)		$9.58
Portland Cement / 94 pound bag (1 cubic yard)		6
Total Concrete Cost		$11,259.18
Cost Per Square Foot		$9.38
Labor		
Operators		4
Alaska Hourly Rate (3)		$26.51
Total Hours (assemble + operations)		30
Total Labor Cost		$3,181.20
Cost per square foot		$2.65
3D Printer		
Unit Cost (4)		$400,000.00
Annual Maintenance	10%	$40,000.00
Life Days		1,825
Daily Rate (Cost / Life Days)		$372.60
Days Used		3
Total Printing Equipment Use Cost		$1,117.81
Cost Per Square Foot		$0.93
TOTAL COST		$15,558.19
TOTAL COST PER SQUARE FOOT		$12.97

(1) Assume equipment rental similar to conventional construction, e.g., mixer,
excavator, generator, water pump, bobcat, etc.
(2) Lowes Fairbanks Alaska Titan Type 94 pound bag
(3) BLS Gov Alaska May 2020 State Occupational and Wage Estimates cement masons and concrete finishers mean hourly rate
(4) Estimated price for Robotic Arm 3DCP and Spare Parts, based on data collected; Price also includes cost of shipping printer from East Coast of lower 48 States to Fairbanks

Alaska Conventional Construction vs 3DCP Housing Units Production Comparison

The conventional construction prototype structure cost of $51.38 per square foot cost is only material and labor cost. Required time for conventional construction is an important fact to compare with 3DCP. Comparing the crew required for conventional construction to a 3DCP construction crew, the number of houses built is vastly different. A typical conventional crew requires a minimum of one to two months to put in a foundation and frame a house and most often three to four months. The 3DCP crew requires only two to three days (after pilings have been put in place) to put in foundation and build the shell of a house. Thereafter, the interior finish requires the same time for both and can be done inside during inclement weather. During the Alaska outside construction period, one conventional construction crew can build two house exteriors while one 3DCP crew can build thirty-two house exteriors. Over five years during a four-month construction seasons, the 3DCP house construction production advantage is dramatic.

Figure 48 AK House Production Comparison



In summary, this Cost Benefit Comparison results in the following key points:

- The estimated cost per square foot for constructing the exterior of a 1200 square foot housing structure is $12.97 for 3DCP, vs $51.38 for conventional construction, based on the RS Means survey cost of construction materials and labor in Fairbanks. Considering that the same market basket of construction materials, labor and transportation in rural areas of Alaska, such as Nome, Bethel and Barrow, is significantly more expensive than Fairbanks, the advantages of 3DCP in those areas would be that much greater.

- Due to faster construction time, 16 times more 3DCP houses can be built compared to conventional construction over a five-year period with one construction crew each.

- Since many 3D printers are easily transportable, the one selected for 3DCP in rural Alaska can be sent to the lower 48 States for continued use after the conclusion of each construction season, and returned the following year.

- Construction by 3DCP results in far less injuries than conventional construction.

- Structures made by 3DCP can have similar thermal insulation characteristics as conventional construction. The floors, walls and roof of 3DCP structures can be filled with additional insulation to meet all required R-Values for rural housing in Alaska.

- Due to 3DCP capacity to quickly build more structure exteriors than conventional construction in a year, compared to conventional construction, 3DCP has the potential to create more jobs, including skilled jobs (carpenters, plumbers, electricians) for Alaskans building interiors for many structures instead of just a few by conventional construction methods.

Task 5 End Notes

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TASK 6: PROGRAM PLAN FOR PHASE 2

The purpose of this Task is to prepare a program plan for Phase 2, as a proposed follow-on to this Research and Feasibility Study. The purpose of Phase 2 would be to use a 3D concrete printer to build a complete model house at a selected site in rural Alaska, to demonstrate, test and evaluate the advanced construction techniques, actual cost-benefits and scalability of 3D concrete printing as a means of providing high-quality, affordable and sustainable housing in different areas of rural Alaska.

Phase 2 would enable all of the steps required to plan and construct a 3D printed house, start to finish, and all of the assumptions and findings set forth in this Research and Feasibility Study, to be field-tested and validated, including:

- Architectural design and engineering (functionality, structural integrity, environmental suitability, comfort, cultural and community aesthetics and lifecycle cost);

- Market analysis, site selection and building permits;

- Availability of local geologic resources for use as aggregate in the concrete mix, and ability to secure the appropriate government permits to extract them for such use;

- Logistics (timely and cost-effective transport, setup and operation of requisite equipment, materials, supplies, work force, power, water, etc. at a remote construction site);

- Reliability of 3D printing equipment and materials, and ability to 3D print a model house in adverse weather conditions in the expected timeframe and with the desired quality of construction;

- Ability to determine the true cost of 3D concrete printing specific to the construction location in rural Alaska, and accurate comparison of such costs to conventional building methods;

- Ability to "stress-test" and evaluate the 3D printed model house through all seasons over the course of a year or more, to determine its ability to meet the rigorous structural, functional, quality and comfort requirements of a residential home in the Alaskan Arctic.

Determine Each Task and Its Duration and Sequential Order to Concrete 3D Print a Complete House at a Rural Alaska Site, to be Selected.

Task 1: Conduct a market analysis for the selection of an optimal location in rural Alaska for the construction of a model house, approximately 1200 square feet in size. An assessment of land acquisition (purchase or lease) and construction requirements for the prototype housing structure, as well as the availability and accessibility of local geologic resources for construction material, will be included in the market analysis. Once the optimal location is identified, conduct a site selection analysis to determine potential sites, ranked in order of availability and preference, and then take the necessary steps to secure the land, subject to obtaining all authorizations required to build, test and evaluate the prototype housing structure. Close collaboration with the appropriate housing authority, local government leadership, tribal and community representatives will be essential for completion of this Task, considering the range of legal, regulatory, engineering, business and financial issues to be addressed, along with obtaining acceptance from the local community, with respect to the land acquisition, accessibility of suitable local geologic resources for construction material, design and construction of the housing structure and plans for its use once construction has been completed.

Task 2: Support the development of permitting criteria for 3D concrete printed housing structures that meet the engineering requirements of State and local building codes, and secure the permits necessary to construct, test and evaluate the prototype housing structure. A longer-term objective of this Task is to support the development of model building codes for 3D concrete printed houses and other building structures in Alaska. Close collaboration with the Alaska Housing Finance Corporation, local and regional housing authorities, the Alaska Department of Commerce, Community and Economic Development and other government Agencies will be required for successful completion of this Task.

Task 3: Conduct a comprehensive requirements analysis and develop an architectural plan for a model house with 3D printed shell and complete interior finishing. Design and engineering focus for the model house will include habitability, functionality, environmental suitability (e.g., non-heat transferring foundation if it is to be constructed on permafrost), structural integrity (e.g., compression, tensile and torsional strength of the structure designed to withstand damage from heaving permafrost, earthquakes, snow loads, freeze - thaw cycles, wind, etc.), comfort (e.g., ensuring the insulation for floors, walls and roof meet or exceeds required R-values, vapor barriers to mitigate condensation, ventilation, etc.) aesthetics (e.g., acceptability of the design, shape and features of the model house) and lifecycle cost (acquisition as well as operation and maintenance). Review design and engineering work conducted by PSU in the Research and Feasibility Study in the context of plans for the model house, particularly with respect to the following:

- Superstructure shape (walls and roof);
- Foundation and floor system;
- Fault system;
- Pile system;
- Adjustable joint system;
- Insulation; interior / exterior finish;
- Interior planning and related issues such as the locations of openings to accommodate entrance, light, views, ventilation, clean water intake, gray water output, kitchen and bathroom placement and functionality, overall efficiency and other considerations.

Extensive engagement from start to finish with local tribal and community leadership and local citizens, to ensure that the planned model house is consistent in necessary respects with local requirements and desires will be essential for the success of this Task, as will consultation and collaboration with expert organizations such as the Cold Climate Housing

Research Center and the Alaska Native Tribal Health Consortium, who have deep expertise and decades of experience working with communities in rural Alaska on residential housing and related matters.

Task 4: For the site selected, determine the optimal mix of local geologic material (rocks, gravel, sand, etc.) with the appropriate (and preferably locally obtainable) cementitious additives and possibly other ingredients to achieve the required structural characteristics for the printed structure. Contract with a qualified engineering firm or University with expertise in materials science, construction engineering and/or additive manufacturing to conduct further analysis in this regard, which may also include testing of additional ingredients for possible incorporation into the mix, e.g., fibers to increase tensile strength, cork, recycled materials or foamed concrete to increase the insulation properties and decrease the weight, and other materials where appropriate.

Task 5: Secure an appropriate 3D concrete printer and print a scaled-down housing structure prototype based on the results of Tasks 2, 3 and 4 in a controlled setting such as a manufacturing facility or laboratory); and conduct extensive stress testing and analysis to determine its conformance with the requirements established in Tasks 2, 3 and 4, and any needed modifications prior to printing a full-sized model house at the site secured in Task 1 in Alaska.

Task 6: Plan and execute the transport, setup and operations of a 3D concrete printer and all associated equipment, materials, supplies, construction management and labor to the rural Alaska location selected in Task 1, along with the necessary technical and onsite support, to print the complete shell of a model house, approximately 1200 square feet in size, based on the results of Tasks 2, 3, 4 and 5. In addition to the 3D printing, secure arrangements with local Alaska suppliers and contractors to procure and install the interior finishing for the model house in accordance with the architectural plans. All contractors and suppliers will be vetted through the local communities or housing authorities. To the maximum extent possible, the design and functionality of the model house and its interior finishing will reflect the results of the requirements analysis and citizen engagement described in Task 3, and collaboration with the local housing authority.

<u>Task 7</u>: Once the 3D printed construction of the model house is complete, determine its true cost, specific to the construction location in Alaska, and develop an accurate comparison to the cost of constructing the same house at the same location using conventional manufacturing.

<u>Task 8</u>: Conduct extensive testing and evaluation of the model house over the remaining period of the contract to determine its sustained ability to meet the requirements established in Tasks 2 and 3. This testing should be done through a combination of the following: 1) periodic local inspection, 2) periodic inspection of the site and structure by qualified structural engineers; and 3) remote sensing and data collection via embedded sensors in all areas of the housing structure deemed to require testing and observation.

<u>Task 9</u>: Develop architecture and engineering plans for a fully functional, self-sustaining 3D printed village in a remote location. Areas of focus for the village plan, in addition to housing units for local residents, will include requisite infrastructure, technologies required for self-sustainability (e.g., food, water, sanitation, energy production, etc.). As with Task 3, engagement with local citizens and other stakeholders will be essential from start to finish for the success of this Task.

<u>Task 10</u>: Develop an education and training program for the community and potential employment in the field of 3D concrete printing of houses, buildings and other structures. The program would provide essential education and training for those interested in entering the field of 3DCP, either as an owner / operator or as a potential employee to operate, maintain and repair the 3DCP printers and associated equipment, as well as care, maintenance and repair of the 3D printed home.

<u>Task 11</u>: Plan and execute an international conference to be held in Anchorage or Fairbanks in showcasing Alaska's application of 3D concrete printing technology to affordable, high-quality, sustainable housing, along with other technologies that might be integrated with the house to enhance health, safety and sustainability.

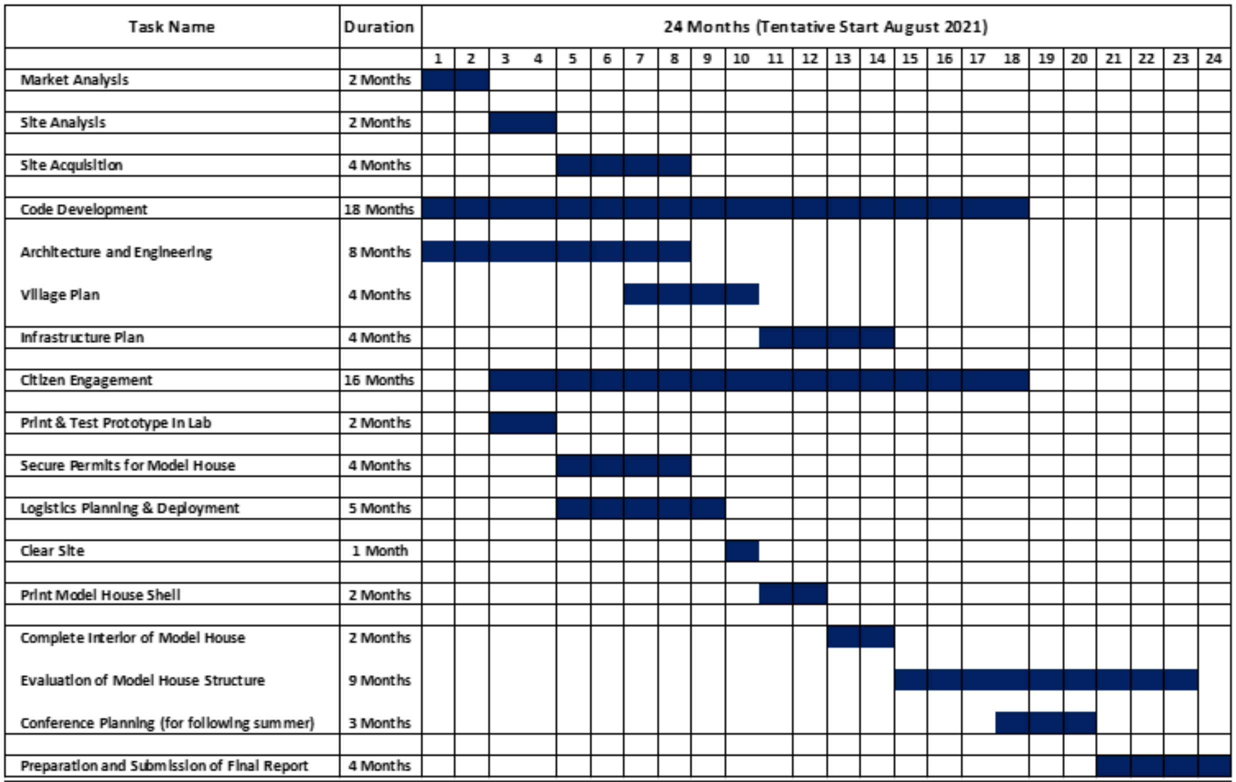
<u>Task 12</u>: Prepare a comprehensive Report including a review of each Task and associated results, along with findings, architectural and village plans, and recommendations for path forward with regard to the viability of 3D concrete printing as a cost-effective means of meeting the varying housing needs of residents in rural Alaska. These findings will include stakeholder reviews and revisions.

The following Tables show estimated costs and timelines for Tasks 1 through 11 in this Phase 2 proposal, to be undertaken and completed over a two-year period. Note that these costs are for budgetary purposes; actual costs may vary.

Figure 49: Estimated Costs for Each Task and Required Resources

Task 1	Market Analysis for a Site	$20,000
	Site Analysis	$20,000
	Site Acquisition	$100,000
Task 2	Code Development	$50,000
Task 3	Architecture and Engineering	$100,000
	Citizen Engagement	$75,000
Task 4	Materials Optimization	$35,000
Task 5	Print / Test Prototype at Lab	$50,000
Task 6	Secure Permits	$25,000
	Logistics and Deploy	$75,000
Task 7	Print Model House on Site	$75,000
	Interior Finishings	$100,000
Task 8	Test / Evaluate Structure	$75,000
Task 9	Village Plan	$20,000
	Infrastructure Plan	$25,000
Task 10	3DCP Training Program	$25,000
Task 11	Conference Planning	$20,000
Task 12	Final Report	$65,000
	Sub-Total:	$955,000
	Robot:	$400,000
	Staffing:	$497,120
	Overhead:	$143,250
	Total:	$1,995,370

Figure 50: Gannt Chart Showing Estimated Schedule for Each Task and Sub-Task:



<u>Final Deliverables:</u>

- Market and site analysis for selection of optimal location for 3D printed house;
- Requisite permits and long-term strategy for code development;
- Optimization of 3D concrete mix including use of local geologic resources for construction of model house at selected site;
- One 3D concrete printed prototype housing structure, constructed in the laboratory;

- One 3D printed model house, complete with interior finishing, constructed on-site at a selected location in rural Alaska;

- Testing and evaluation of the prototype and the model house;

- Development of plans for a self-sustaining 3D printed village in rural Alaska;

- An education and training program for Alaskans interested in 3DCP for business or employment opportunities;

- Planning of international conference on 3D concrete printing and associated technologies;

- A comprehensive Report of the results of Tasks 1 through 11;

- Recommendations and for path forward with regard to the scale production of 3D concrete printed houses and associated infrastructure to meet the need for rapidly deployable, high-quality affordable housing in rural Alaska.

APPENDIX A:

Pennsylvania State University AddConLab Design and Engineering Analysis

APPENDIX A:

PennState
AddConLab

The Additive Construction Laboratory (AddConLab) is a multidisciplinary, collaborative effort between the College of Engineering and the Department of Architecture with a mission to explore various aspects of the use of additive manufacturing at construction scale. It addresses a multitude of issues concerning the design of materials, printing system, toolpath, structure, and building design. The laboratory is housed at Civil Infrastructure Testing and Evaluation Laboratory (CITEL), satellite research facility of the University Park Campus at the Pennsylvania State University.
Website: < https://sites.psu.edu/addconlab/people/>
Address: 3127 Research Drive
State College, PA 16801,
United State

Analyses of concrete samples with ingredients and engineering analysis of concrete 3D printed box shaped housing structure

Sponsored by: Xtreme Habitat Institute and
the Alaska Housing Finance Corporation

May 9th, 2021

Memari, A. M., Bilén, S., Brown, N., Duarte, J. P., Nazarian, S., Radlińska, A., and Xiao, M.

Abstract

The objective of this project is to explore the feasibility of 3D printing concrete homes in Alaska for permafrost regions. The project is developing conceptual design schemes for a small building with approximate dimensions of 12 ft × 12 ft × 10 ft, with shape and configuration suitable for 3D printing of the entire structure. The feasibility study considers both applicable loads on the structure (self-weight, snow, wind, earthquake) and thermal aspects of the structure and foundation. It is of primary concern to avoid heat transfer between the structure and the supporting ground, and this drives the configuration of the design, which foresees the creating of a crawlspace to allow air circulation between the top of ground and the underside of the structure. While this is the preferred solution at this point, the study is also looking into the option of having a slab on grade design, such that crushed rocks and insulation assist in avoiding the transfer of heat to the permafrost. For the elevated design with the crawlspace feature, it is assumed that the printed concrete columns will be located on top of wooden or steel piles that extend through the active layer and into the permafrost zone. The project also includes developing material test results, such as compressive strength and modulus of rupture, based on the concrete cylinders provided to us. As the project evolves, we intend to address cultural values and maintain high standards regarding architectural design and the aesthetics of the 3D-printed structures, while considering local building regulations and materials, technical issues related to additive construction, engineering of the structural and environmental systems, and proper insulation and finishes.

Table of Contents

Xtreme Habitats: 3D Printed Alaskan Rural Homes Phase 1 -- Feasibility Study Final Report

May 9th, 2021

Introduction

Review 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 earthquakes. Moreover, energy efficiency and health aspects are of primary interest as well. Various documents (e.g., CCHRC 2014,) have been developed by Cold Climate Housing Research Center (CCHRC), which guide developers, homeowners, government, financial institutions and all stakeholders in developing design and construction practices that consider various critical aspects. For example, CCHRC (2014) lists several desirable guidelines such as use of materials and construction that reduces the time of construction, is healthy to live in, suits the lifestyle of inhabitants, energy efficient, and affordable, among others. Furthermore, given that 40% of the Alaska's 300 communities are in rural areas, without much road access and great many without running water and sanitation, healthy home building becomes a more critical issue for homes in these regions (USDA 2017). This project explores for the first time the feasibility of using 3D printing in rural Alaska considering these goals.

A review of the vernacular architecture in Alaska (HUD 2011), has made clear that in every part of the state, the vernacular architecture was built such that not much fuel was needed in order to keep them warm. Northern Alaska Native People's homes for example, were made cold proof by heavily covering wooden frames with earthen materials. The indoor temperature was always between 60-70 degrees despite the fact that the uncovered opening above the main living area and the cold trap zone were left open to fresh air. However, the influence of typical modern American home construction techniques that were not developed for extreme cold conditions have negatively impacted quality of life. The walls, floors, and roofs, function as thermal bridges, leading to loss of significant interior heat through conduction, and thus conventional heating methods showed to be no longer sufficient to keep the interiors at comfortable temperatures, with the consequence of the rise of many health conditions. In addition, they have been costlier to build and maintain because these houses are hermetically sealed and prevent flow of fresh air, thus requiring air conditioning systems unlike Alaskan vernacular architecture, which promoted natural ventilation and year-round comfort. In addition, much of the required wood for construction purposes would have to be imported, thus more expensive.

Review foundation systems used in Alaska home building

Residential buildings in Alaska use both shallow and deep (i.e., pile) foundations. Shallow foundations are normally defined as footings with width equal to or greater than their embedment depth, which is governed by the thickness of the active layer. In suitable soil conditions, they 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 with or without insulation (Andersland and Ladanyi 1994). It is also general practice to excavate and construct shallow foundations in the fall and allow the cold winter temperatures to freeze back the disturbed subsoil area.

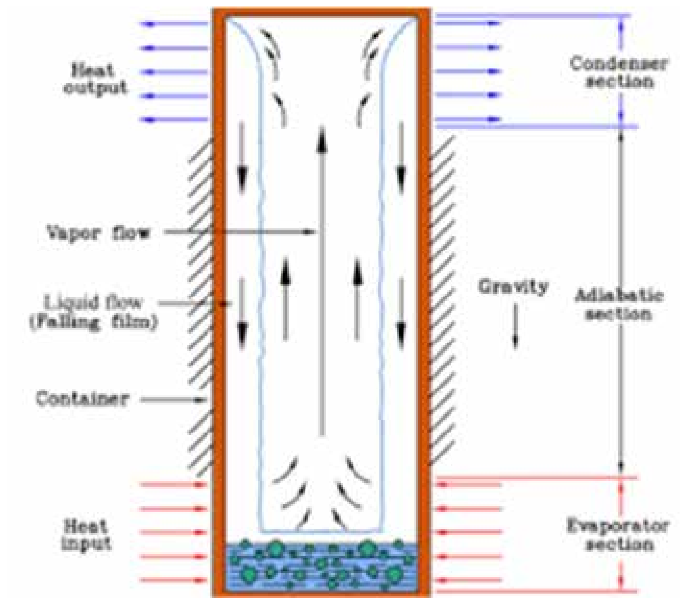
In permafrost regions, pile foundations are predominately used for houses of various sizes (PTF 1998). Pile foundations do not require open excavation, which can significantly disturb the permafrost, accelerate permafrost thawing and causing thermokarst, i.e., marshy hollows formed after frozen ground thaws. Structures supported by piles are elevated above the ground surface for two reasons: (1) to prevent the heat loss through the floor of heated structures from warming the frozen ground, and (2) to allow cold air to refreeze the active layer in the winter. The ventilation space between the floor of a house and the ground surface is generally 0.5 to 1.0 m, but may be taller under heated buildings to prevent degradation of permafrost. The design details of two types of pile foundations on permafrost are presented in a later section of this report. Creosoted wood and steel pipe or H-section piles are the most commonly used types; precast concrete piles are used much less frequently in permafrost in North America and cast-in-place concrete piles are only used occasionally (Linell and Johnston, 1973). When the floor of a structure is large (such as a water storage tank) and cannot be economically supported by pile foundations, slab-on-grade with passive or active foundation cooling systems can be used. A design example of such a foundation is illustrated in a later section of this report.

Frost protected shallow foundation (FPSF) is a type of slab-on-grade foundation where elevated pile system is not desirable or feasible (e.g., due to the need for accessibility or cost); its purpose is to prevent frost heave caused by freezing of the foundation soil. FPSF has a vertical rigid insulation layer around the outer edge of the foundation that extends to the bottom of the foundation wall and a horizontal rigid insulation that extends out from the foundation wall by two to four feet. FPSF is not used on permafrost (CCHRC 2019), because the incorporation of FPSF is to keep the foundation soil from freezing, while the foundations built on permafrost should keep the foundation soil freezing.

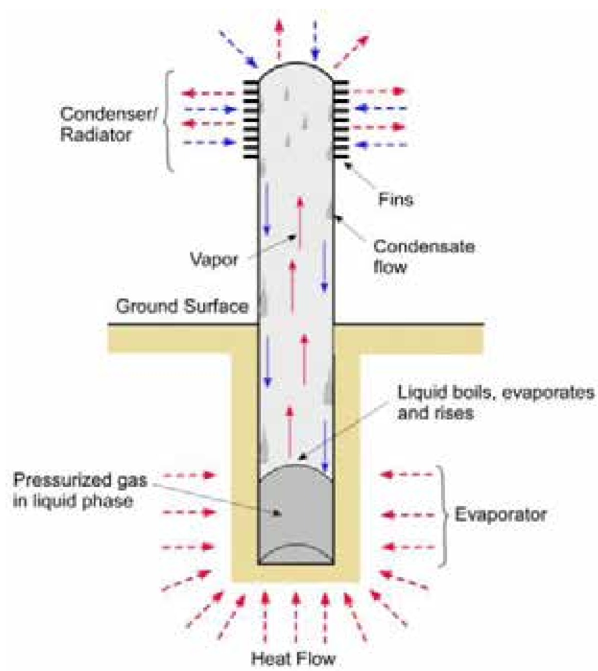
Review permafrost related foundation systems research by Cold Climate Housing Research Center

Proper consideration of the interaction between the building and the frozen ground in permafrost zone can lead to successful design of the home. Permafrost is considered a frozen ground with temperature below 32 for over two consecutive years. On the other hand, if permafrost layer starts to experience heave due to repeated thaw-freeze cycle, the foundation and the structure can have settlement causing damage to the structure. The zone that experiences freeze-thaw is defined as the “active layer”. Therefore, the design needs to prevent the heat transfer between the structure and the soil to maintain bearing capacity of the supporting soil (McFadden 2000). In case the occurrence of heat transfer prevents freezing of the topsoil (active) layer, a layer at the top of permafrost will be unfrozen and can cause settlement. Such settlements need stabilization per guidelines such as those by McFadden (2001).

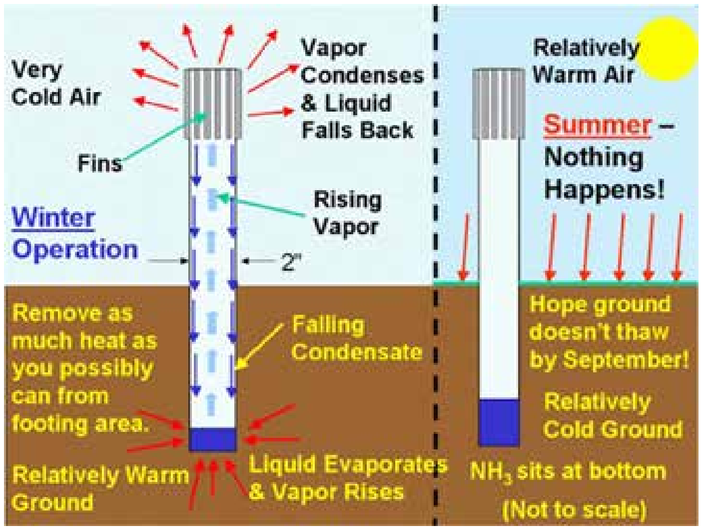
According to an article by Simonelli (2018) interviewing CCHRC staff, the two passive approaches for handling permafrost by minimizing heat transfer between the structure and the permafrost zone include the use of thermosyphons or thermopiles. Thermosyphons (Wagner 2014) are non-load bearing sealed tube installed in the ground under the building or adjacent to it where the top is exposed to air. Ground heat is absorbed by a phase change material within the pipe and is released to the cold air at the top (Figures 1 (a)-(c)). Such a solution is suitable for slab-on-grade system, where a gravel bed that is not susceptible to frost and rigid insulation in addition to non-load bearing thermosyphon are used and can be more economical than pile supported structures.



(a) Example 1 thermosyphon (https://www.thermalfluidscentral.org/encyclopedia/index.php/Two-Phase_Closed_Thermosyphon)



(b) Example 2 Thermosyphon (https://apps.dtic.mil/dtic/tr/fulltext/u2/a595037.pdf)



(c) Example 3 Thermosyphon (https://www.pinterest.com/elsiemjk/thermosiphon/

Figure 1. Examples of Thermosyphons.

On the other hand, thermopiles are more conventional to address permafrost and allow the building to be elevated and provide not only ventilation under the building base but also the elevated structure prevents snow accumulation (under the structures), which reduces the insulating component of the snow covering the ground (i.e., without snow, cold air will reach the ground surface, thus helps keep the ground colder as desired). Thermopiles use passive refrigeration that allow drawing the ground heat around the pile as shown in Figure 2. Thermopiles are further discussed subsequently.

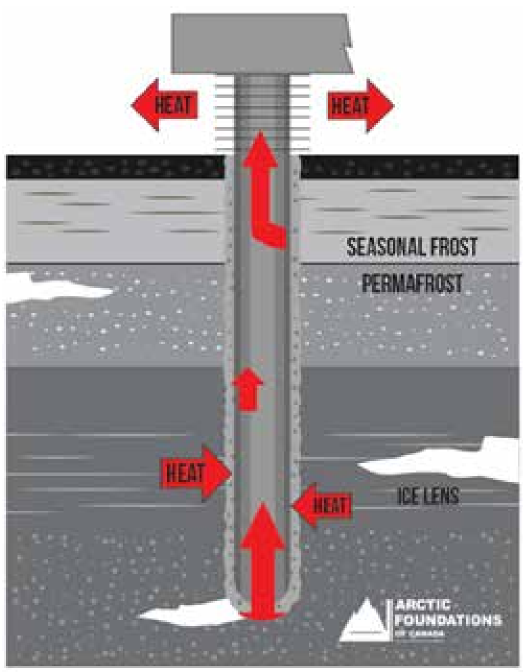


Figure 2. Example of Thermopile (http://arcticfoundations.ca/service/thermopiles/).

Structural System Definition

Our focus in the feasibility phase of this project is on a solution that permits the 3d printing of a full continuous concrete shelter to avoid structural joints as much as possible. In general, given the potential for pile support settlement due to thawing of frozen ground (e.g., active layer and/or top of permafrost zone), leading to heaving and adfreeze conditions, the building should be able to accommodate differential settlement. This aspect will be considered in greater detail in follow-up Phase 2. However, at this stage, we assume any settlement can be adjusted using adjustable jacks that will be assumed placed between piles and the bottom of columns. Given the current state of the art, we may also focus on solutions that avoid complex reinforcement solutions, except for critical components such as foundations, i.e., concrete columns that are partly printed (shell) and partly cast. Our studies so far have focused on design solutions with compressive stresses as the main load resisting mechanism in the walls, which could be printed without formwork using carbon or steel fibers mixed with the concrete mixture as an appropriate reinforcement for 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 in the first stage of our explorations (Figure 3). All these solutions have a footprint of 12′ × 12′ and a height between 8′ and 13′, 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 3 are all assumed to be slab on grade, the same structures are also being considered as elevated options. It should be noted that currently, a few companies that promote 3D printed concrete home building, generally print the walls only, and use conventional roofing systems. However, our preferred designs are based on benefitting from the full potentials of 3D printing in 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, 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 (Figure 4).

Figure 3. 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.

Figure 4. Possibility of clustering several structural units together to create larger houses. There can be different clustering possibilities beyond the one shown.

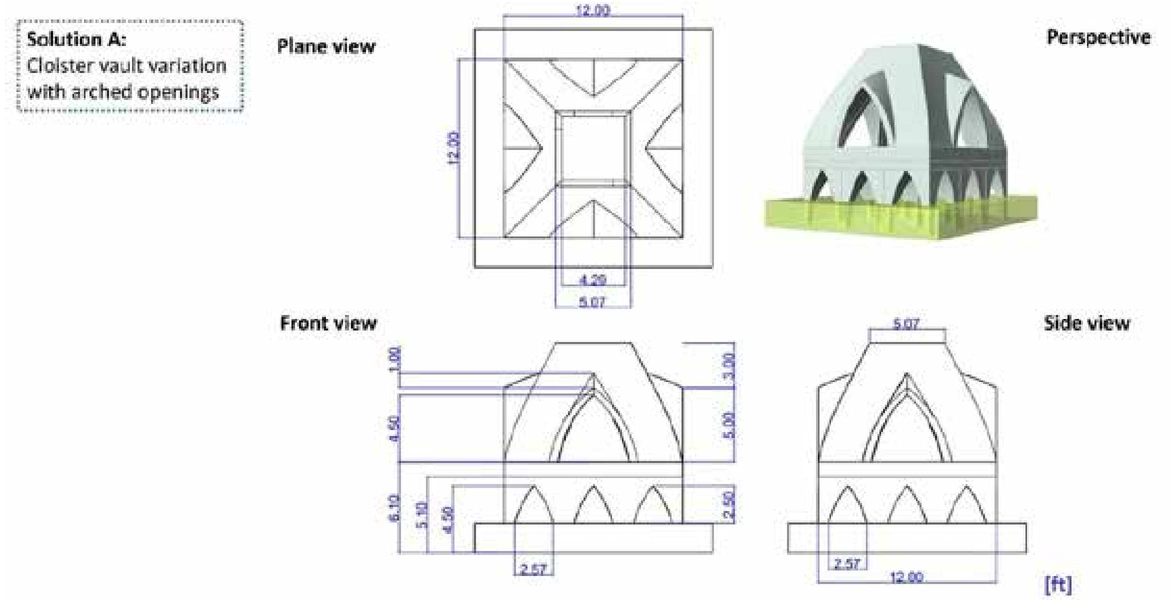


Figure 5. Solution A with a cloister vaulted structure and pointed arched openings.

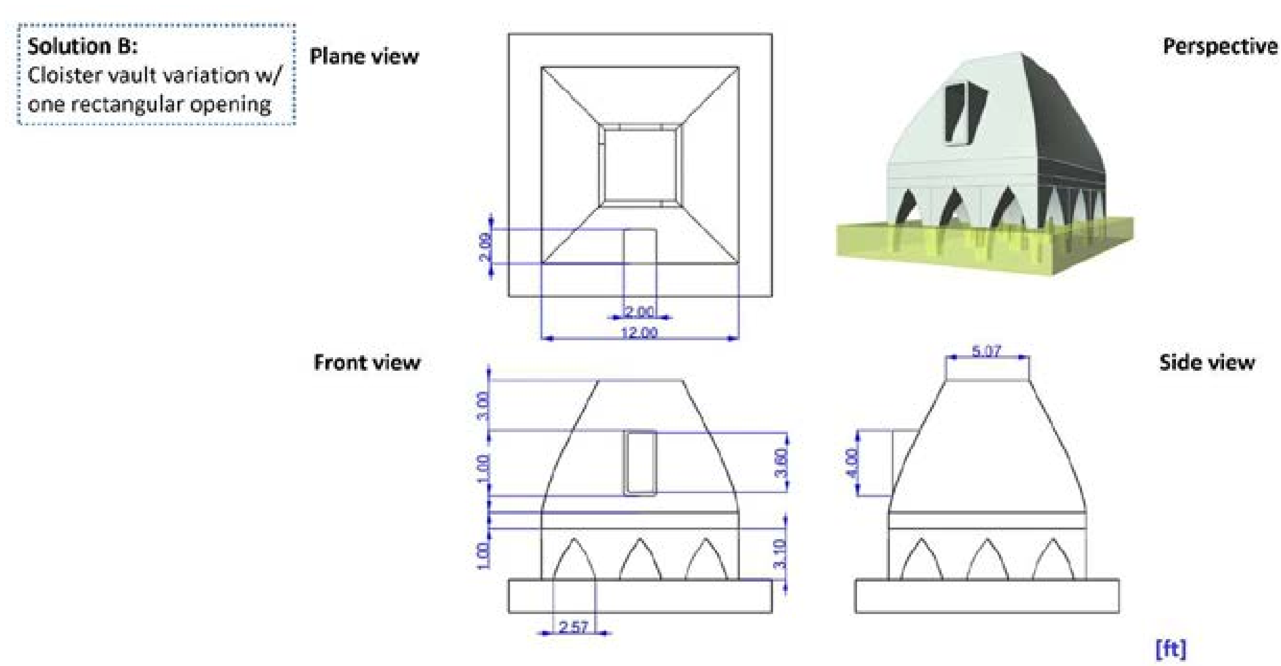


Figure 6. Solution B with a cloister vaulted structure and straight openings.

Solutions A and B (Figures 5 and 6) 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 be used for 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 (Figure 7) is based on a traditional dome shape from ancient Persia, which permits to transition from a square footprint to a round top, with some advantages in terms of 3D printing. Solution D (Figure 8) is based on a cross-vault with pointed arches. It is the tallest of the four structures, but it is also the one that is fully enclosed at the top. Based on preliminary evaluation of the four options for this feasibility study, the team has narrowed down the more desirable designs to two options, B and D, while recognizing that the designs are still subject to extensive analyses in follow-up Phase 2. However, this range of solutions demonstrates the design flexibility of the method and will be used to generate proof of concept.

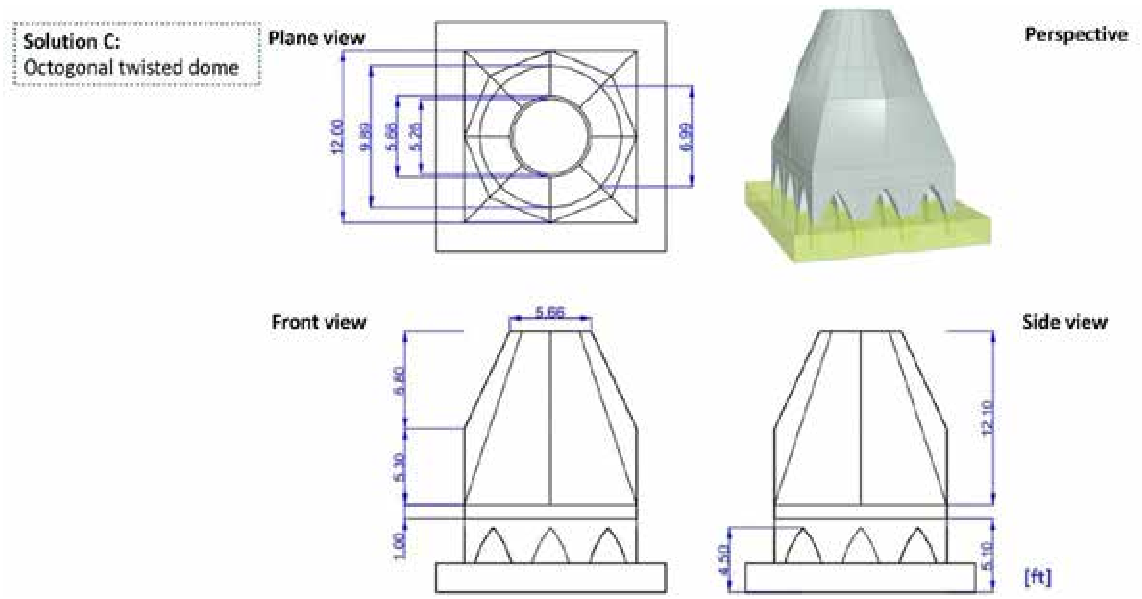


Figure 7. Solution C with a Persian dome structure.

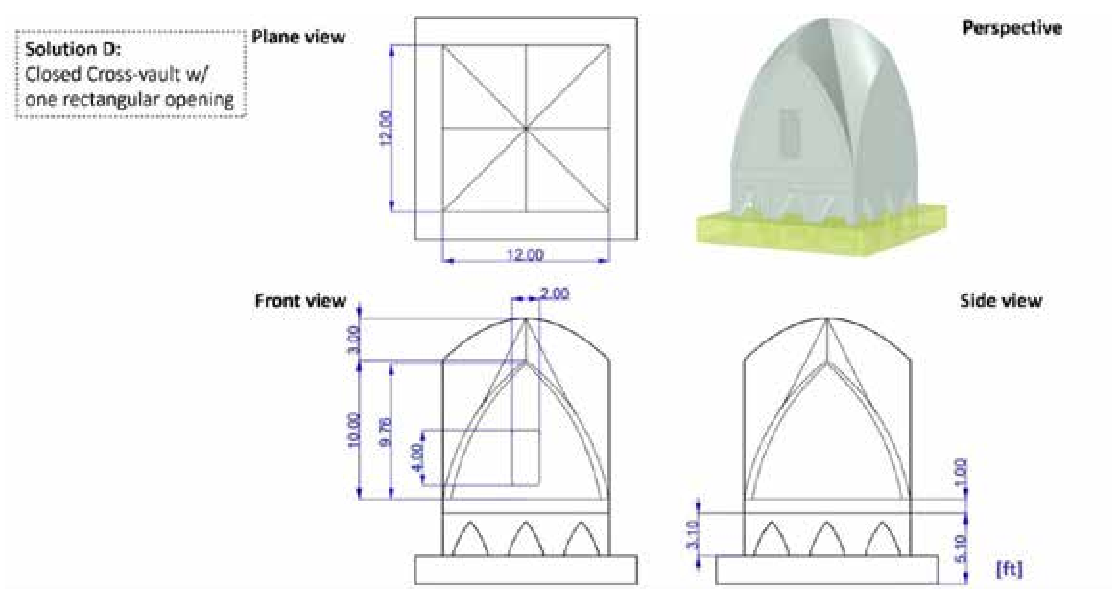
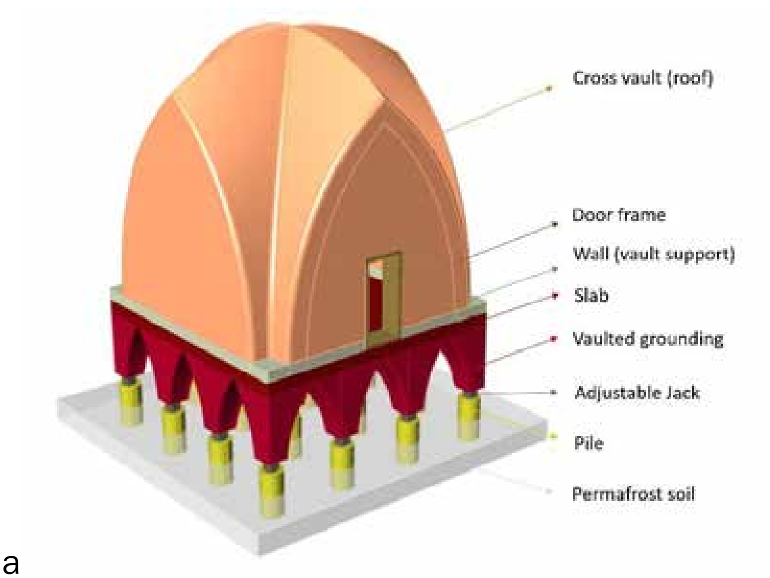


Figure 8. Solution D with a cross vaulted structure.

All these structures are divided into foundation, grounding, slab, walls, and roof (Figures 9 and 10). A parametric definition of the structure allows 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 will constitute 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. This platform will permit one to analyze the tradeoffs between different solutions and to find the ones with better performance from the selected structural and thermal viewpoints.



a

b

Figure 9. Preferred solution, elevated version: (a) 3d model of solution showing the different parts of the 3D printed monolithic structure (piles, grounding, slab, walls, and roof), and (b) the look of the printed structure. A staircase will be added to this solutions.

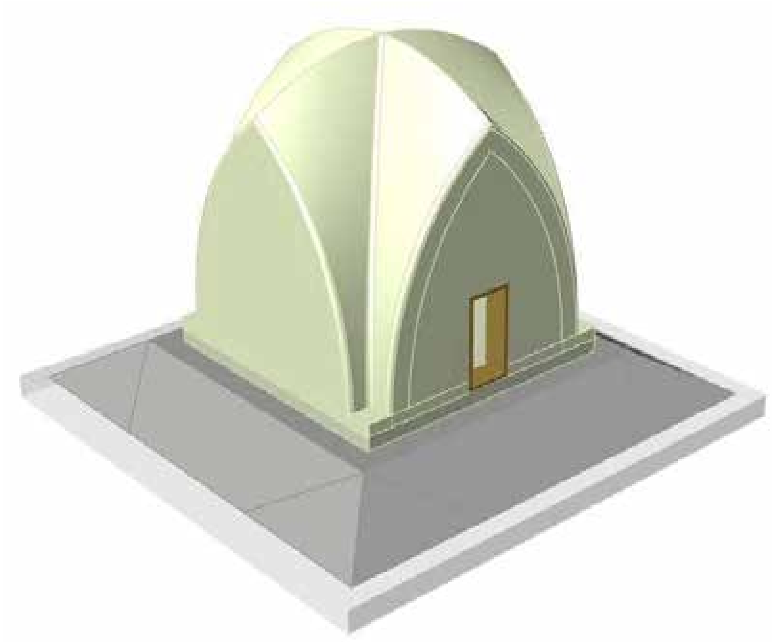


Figure 10. Preferred solution, slab on grade version: the look of the printed structure.

Foundation

Three basic solutions were studied for the foundation, and an additional podium option identified as well. The first solution consists of a floating slab supported directly on the ground as shown in Figures 3 and 10 above. This configuration (also shown in Figure 12 a) presents difficulties posed by the deposited concrete material, including high temperature during curing, which may cause heat transfer to the active layer. Also, this solution makes it difficult to thermally isolate the interior, which is warmer during use, from the cold soil layer. However, it is possible to overcome these difficulties by special design of the foundation, consisting of depositing a bed of crushed stone 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 to the ground. Alternatively, raising the main structure with piles is more effective (Figures 9 and 11). This solution creates an isolating air cavity (as in a crawl space) between the warmer, inhabitable structure and the frozen permafrost soil underneath. Within this category, there are three possible solutions. The second potential solution is to print pillars to form the entire foundation both above and below grade (Figure 12 b). This solution requires the printing system to reach several feet deep in the active layer and within the permafrost region and presents disadvantage of the deposited material, which reaches high temperature while curing, and as mentioned above, may cause heat transfer and potential melting of the soil in the permafrost region. While consideration of this option at this feasibility phase is justified, due to thermal and structural challenges, it is not a desirable option. In the third solution (Figure 12 c), 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 12 d), a concrete slab platform would be printed on top of piles creating a “podium” on which the structure can be printed. Design of connections between the piles and 3D printed concrete will be carefully considered based on seismic and other lateral requirements.

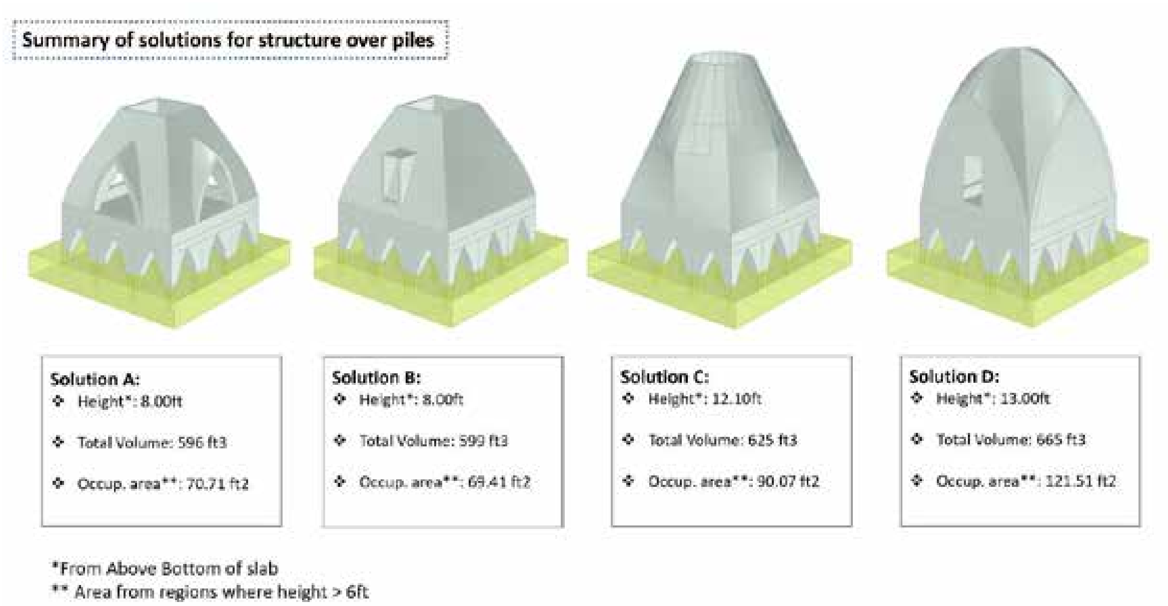


Figure 11. Selected structures. Elevated version with grounding consisting of a set of small cross vaults clustered together to create a crawl space underneath, separating the shelter from permafrost soil.

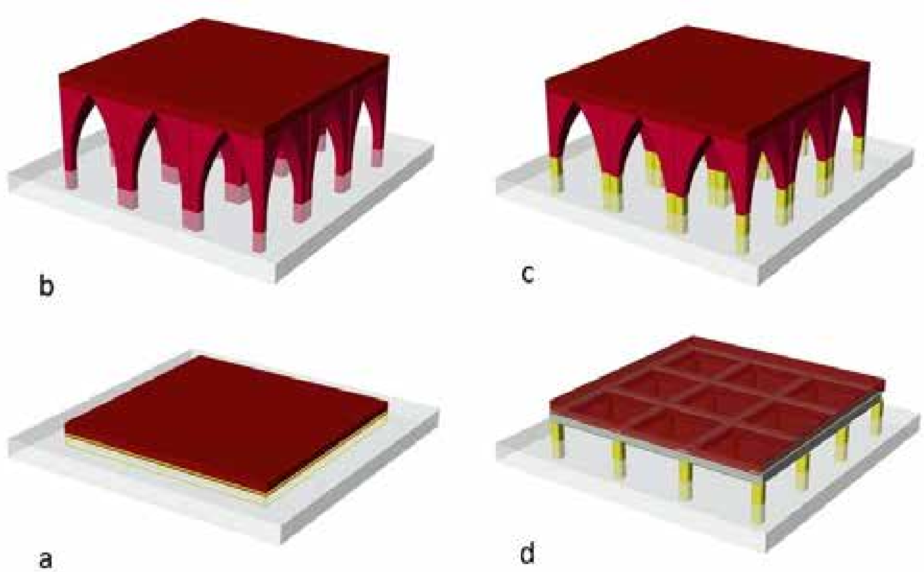


Figure 12. Solutions for the foundation: a) floating 3d printed slab on ground, b) slab on 3D printed concrete grounding on piles in the same material, c) slab on 3d printed concrete grounding on piles in other material (wood or steel), and d) concrete slab 3D printed on cable grid structure.

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. The goal of the design is to enable as much airflow as possible through the cross vaults while still transferring structural loads of the floor slab above down into the individual piles below. These geometric tradeoffs have been analyzed, and the constraints for the needed height to create sufficient ventilation, while limiting the height to reduce lateral seismic induced forces in the columns have been taken into account. Furthermore, considering the height needed for the curved arch shape of the supporting columns, the result has been to minimize the height of the pile above ground surface to about 2.0 ft, with the rest of the height for ventilation provided by the printed columns for a total open space height of about 5 ft above the ground surface.

The shape of the grounding can 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 light-weight concrete where 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, and in the second option, the outer shell and the inner lighter core are printed simultaneously using a technique called functionally graded material printing, where the aggregate content of the mixture is changed during printing. The second solution requires a more sophisticated and costly printing system. Of course, it is recognized that the added insultation provided by mixing cork or other insulation granular materials will be minor compared to the level of R-values needed for Alaska. Nonetheless, such options will be evaluated further in Phase 2 study. For this Phase 1, we will consider foam insulation as explained subsequently.

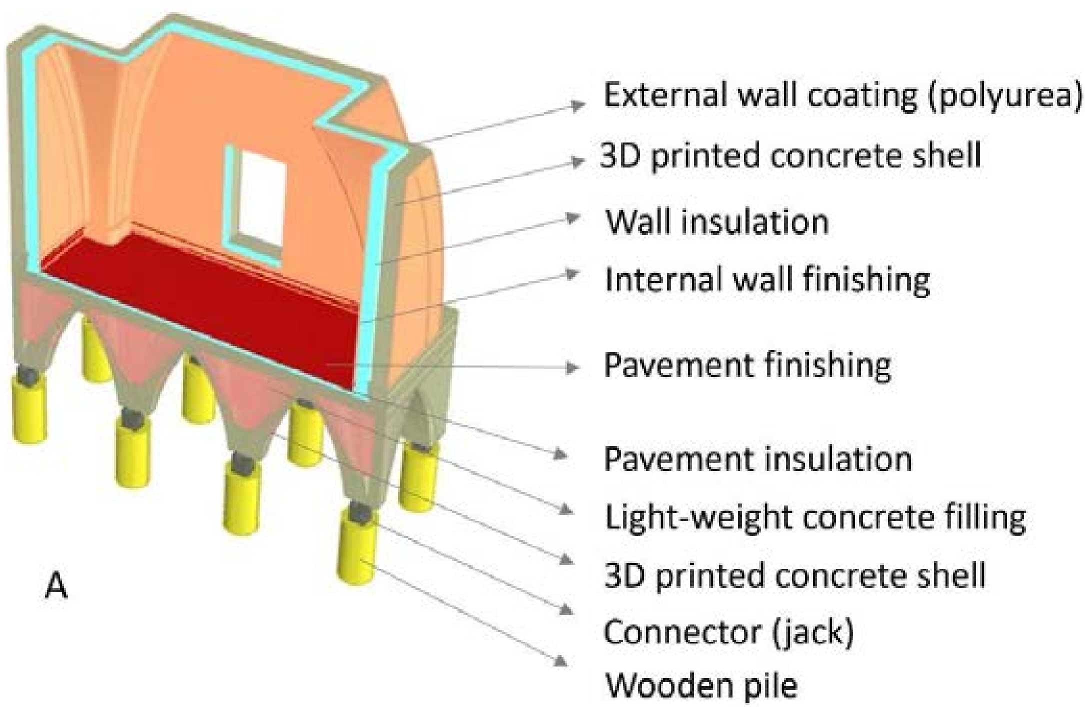
Yet another solution consists of a graded slab mounted on the piles, on the top of which the concrete slab is then printed. This hybrid solution simplifies printing but leads to a more complex shelter by involving other construction systems. Considering that permafrost is the frozen ground zone below the active layer, the structure will be designed to avoid heat transfer to the permafrost soil. This will be shown in greater detail in the foundation design section.

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 optionally functionally graded concrete, where sand aggregates are partially replaced by lightweight expanded clay or cork granules with insulation properties, 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 a functionally graded material may be used even in Alaska construction, significant supplemental insulation will 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 will be considered for the structure of the walls: solid (single shell) or hollow (double shell) (Figures 13 and 14). The former may use homogeneous concrete or functionally graded concrete with insulative “layers” with an increased grade of lightweight (with the potential benefits mentioned), and the insulative aggregates printed on the exterior side of the wall. The latter has the advantage of being lighter, using less material, 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 in Phase 2 will permit to identify the most appropriate solution weighing in structural, thermal, printing, and construction considerations.



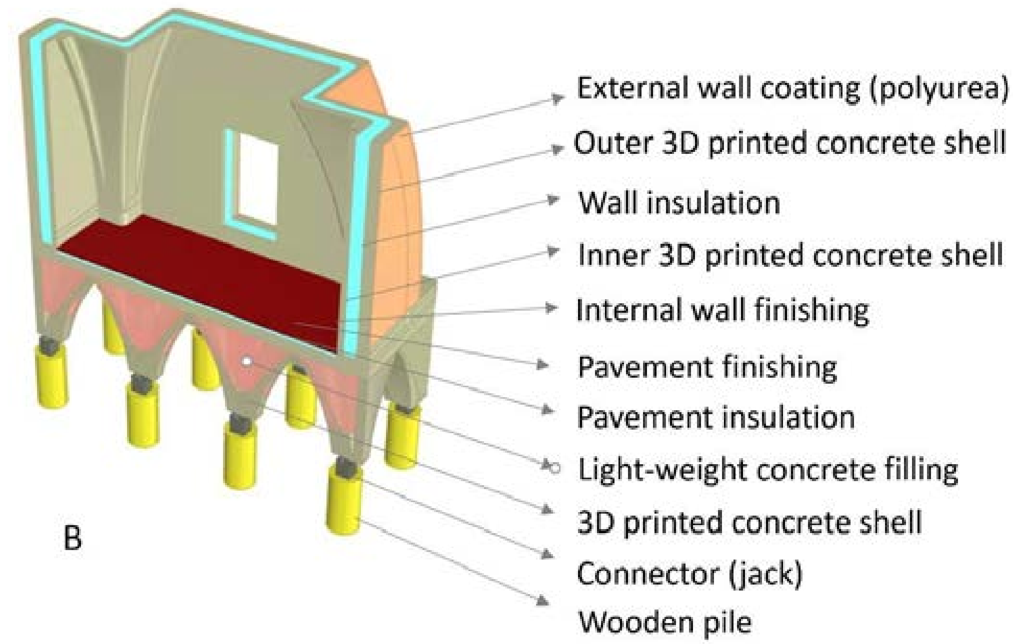
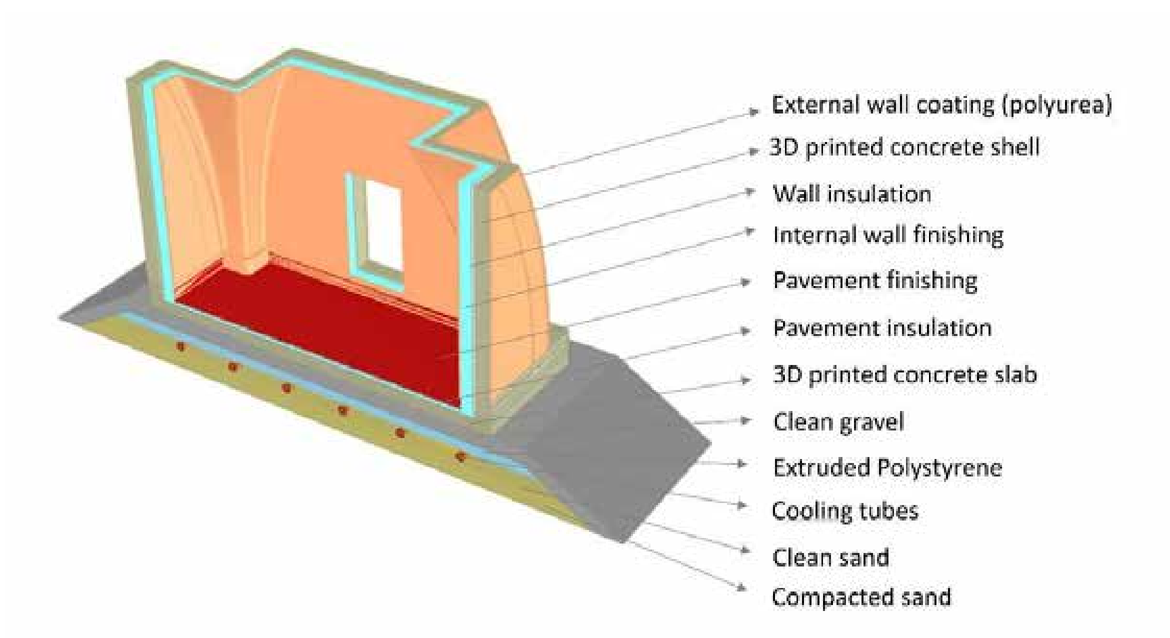


Figure 13. Elevated solution with the two possibilities considered for the structure of the walls and roof: (a) single shell or (b) double shell. (Please note: by pavement, it is meant floor)



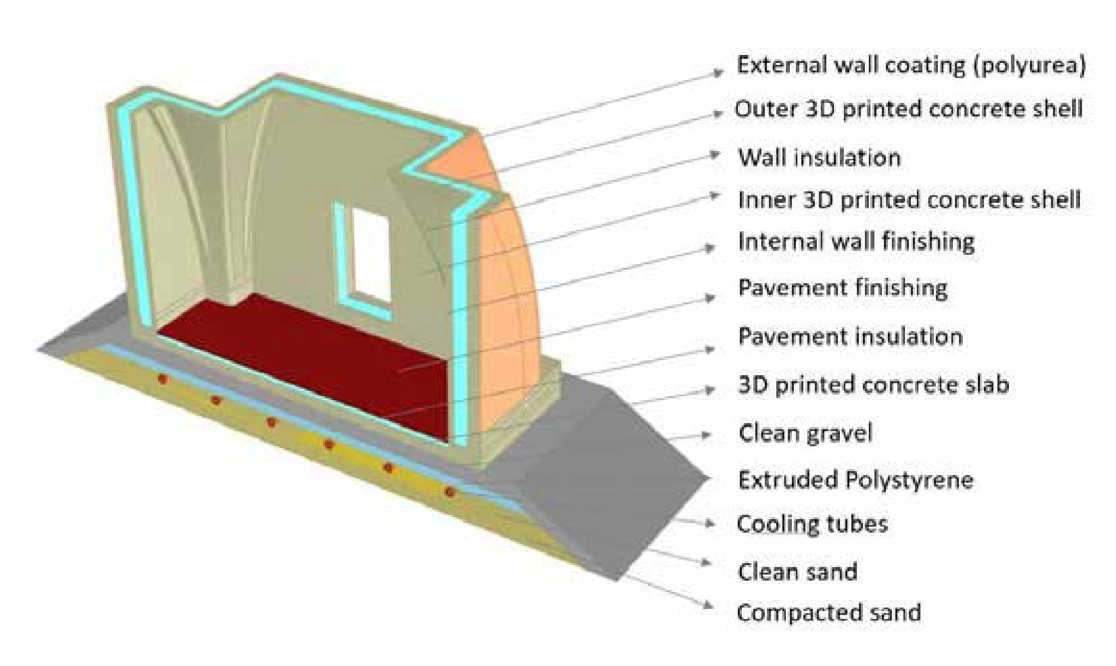


Figure 14. Slab on grade with the two possibilities considered for the structure of the walls and roof: (a) single shell or (b) double shell. (Please note: by pavement, it is meant floor)

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 to 3d printing of the whole structure, avoid formwork, simplify construction, and provide a sealed-enclosure 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 & Insulation

In addition to the structural requirements, the environment in Alaska necessitates careful consideration of the envelope and its performance. A central issue is thermally separating the conditioned indoor space from the foundation through an open crawlspace to avoid melting the permafrost. While thermal separation for the floor is discussed elsewhere in terms of structural effects, it also relates to the livability of the house. The surface temperature of the floor is of particular concern in Arctic climates, since it is where occupants work, play, and relax. Insulation that isolates the foundation from the living space will also be evaluated in terms of its ability to keep the floor surface temperature as close to the ambient temperature as possible. This will reduce thermal discomfort from radiation and stratification of cold air near the floor.

In addition to the floor, the walls and roof have stringent insulation requirements. For Alaska 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, including rigid foam insulation, thick fiberglass batts, insulated concrete forms (ICFs), structurally insulated panels (SIPs), or dense-packed fiberglass or cellulose (Figure 15). The geometries produced by 3d printing may require different strategies due to their curvature and often gradual transitions between what is considered a wall and what is a roof.

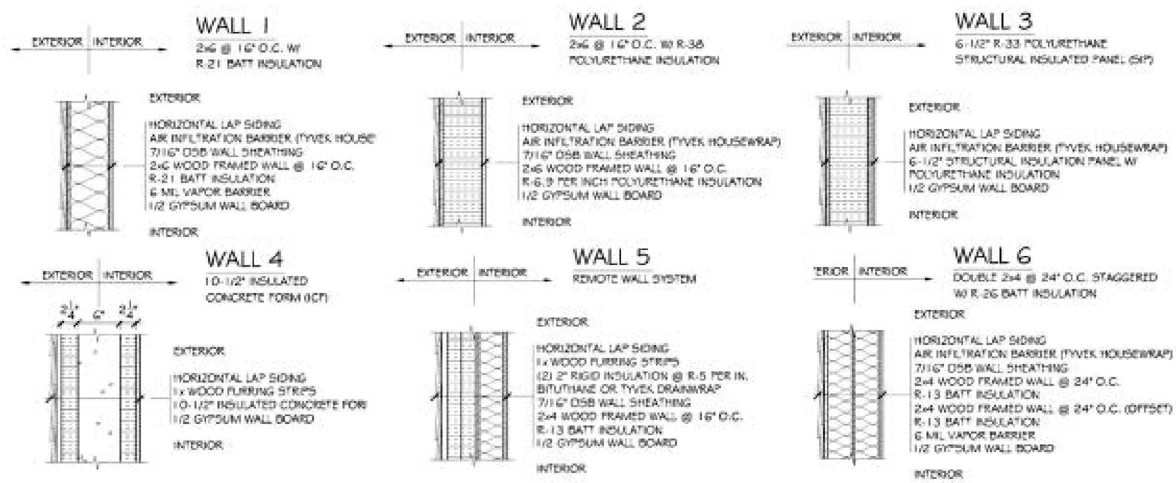


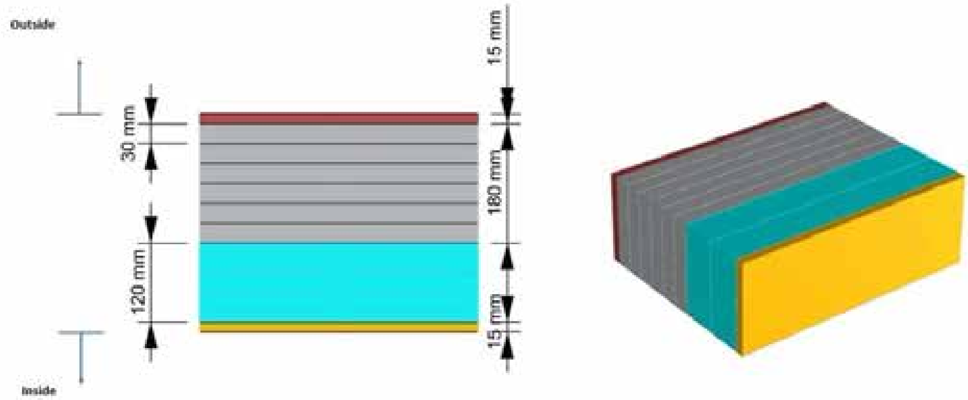
Figure 15. Typical wall assemblies for Alaskan construction.

Given these challenges, several insulation approaches can be considered. Besides the conventional single material in a given layer, functionally graded materials offers a solution to integrate cork or other lightweight and insulation materials (e.g., styrofoam balls) into the concrete to improve various properties and attributes, including lightweight that favorably affects foundation design and seismic design, improved thermal resistance, and lower carbon footprint, thus being more environmentally friendly. However, since concrete itself generates less than R-1 per inch depending on density, other insulating materials will be required. One possibility is spray foam, which can adhere to custom shapes and offer R-values of up to 7 per inch for closed-cell foams (Strategy 1 in Figure 16). Another option is to print double walls and even roofs, which creates some structural advantages, and then fill the voids/cells with insulative materials. Such a double wall solution would behave analogously to a structurally insulated panel but will follow the concrete shape rather than the usual modular form of a panel system (Strategy 2). In this method, special care would be given to potential thermal bridging, subject to how the two layers are connected to ensure structural load transfer. Depending on final geometries, some options might also be combined—for example, some of the flat portions could contain rigid insulation to save on costs, as long as a continuous thermal barrier can be maintained.

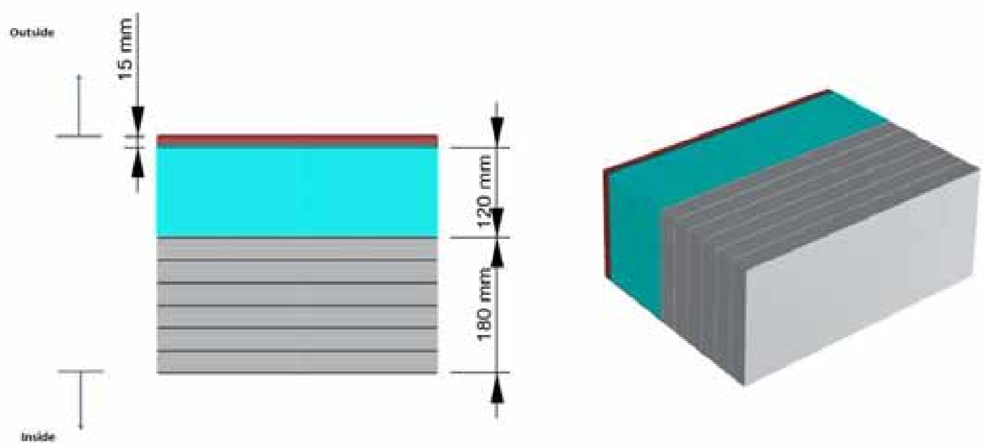
Item A.

1. Single shell

a. Insulation inside



b. Insulation outside



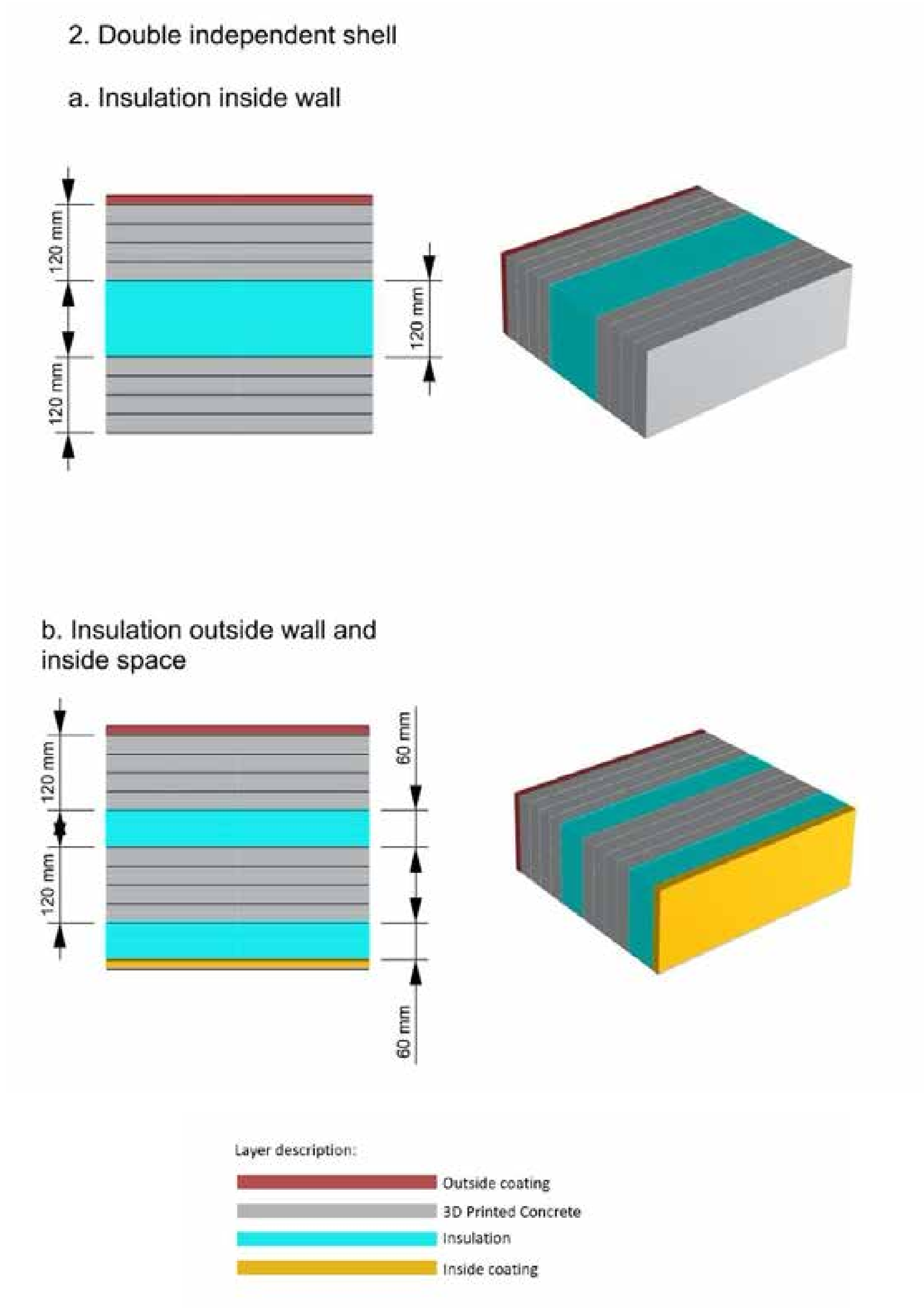


Figure 16. Potential thermal insulation strategies: considering the printing of a single or a double shell and the placement of the insulation layer, inside, outside, in between the shells, or a combination of both.

Preliminary R-value calculations for the assembly concepts are provided in Table 1 below. Besides these assemblies, double wall configurations that include straight or curved ribs are also possible to design for. However, such designs need innovative concepts to minimize thermal bridge in order to increase overall section R-value, and for this reason, such a solution is not addressed in this feasibility study, but can be considered in Phase 2. The estimated R-values can also be compared to requirements for ceilings and walls for Alaskan climate zones (Table 2). Especially for the insulation-inside configuration, the spray foam could be thickened as the wall transitions into a ceiling where necessary. For the double shell configuration, this transition could also be made but will be accomplished through a combination of decreasing the shell layers and widening the gap.

Tables 1. Calculated overall insulation for single and double walls

	Material	R-value per inch	R-value	Thickness	R-Value Total
		(Range)	(Used)	in	Deg F x ft^2 x hr / BTU
1 - Single Shell	Air film (inside)				0.68
	Interior Finish				--
	Spray Foam	5 to 7	6.25	4.72	29.50
	Concrete	0.07 to 0.52	0.21	7	1.47
	Exterior Finish				0.50
	Air film (outside)				0.17
	Total				**32.32**
2 - Double shell	Air film (inside)				0.68
	Interior Finish				--
	Concrete		0.21	4.72	0.99
	Spray Foam	5 to 7	6.25	4.72	29.50
	Concrete	0.07 to 0.52	0.21	4.72	0.99
	Exterior Finish				0.50
	Air film (outside)				0.17
	Total				**32.83**

Tables 2. Alaska Insulation Requirements

Alaska Insulation Code Requirements	Ceiling	Wall
Regions 1-3 (Southeast, southcentral, Interior southwest)	38	18-25
Region 4 (Northwest)	38	30
Region 5 (Arctic Slope)	52	35
*ahfc.us/iceimages/manuals/building_manual_ch_02_special_considerations.pdf		

Foundation System Definition

Pile supported structure option elevated from ground

Two pile foundations are typically used in permafrost regions:

1. Slurried pile foundation (Figure 17) where predrilling is required, and freeze-back time is required to fully freeze the slurry before loading can be applied.
2. Driven piles (Figure 18) where preheating a pilot hole may be needed to drive a pile into permafrost.

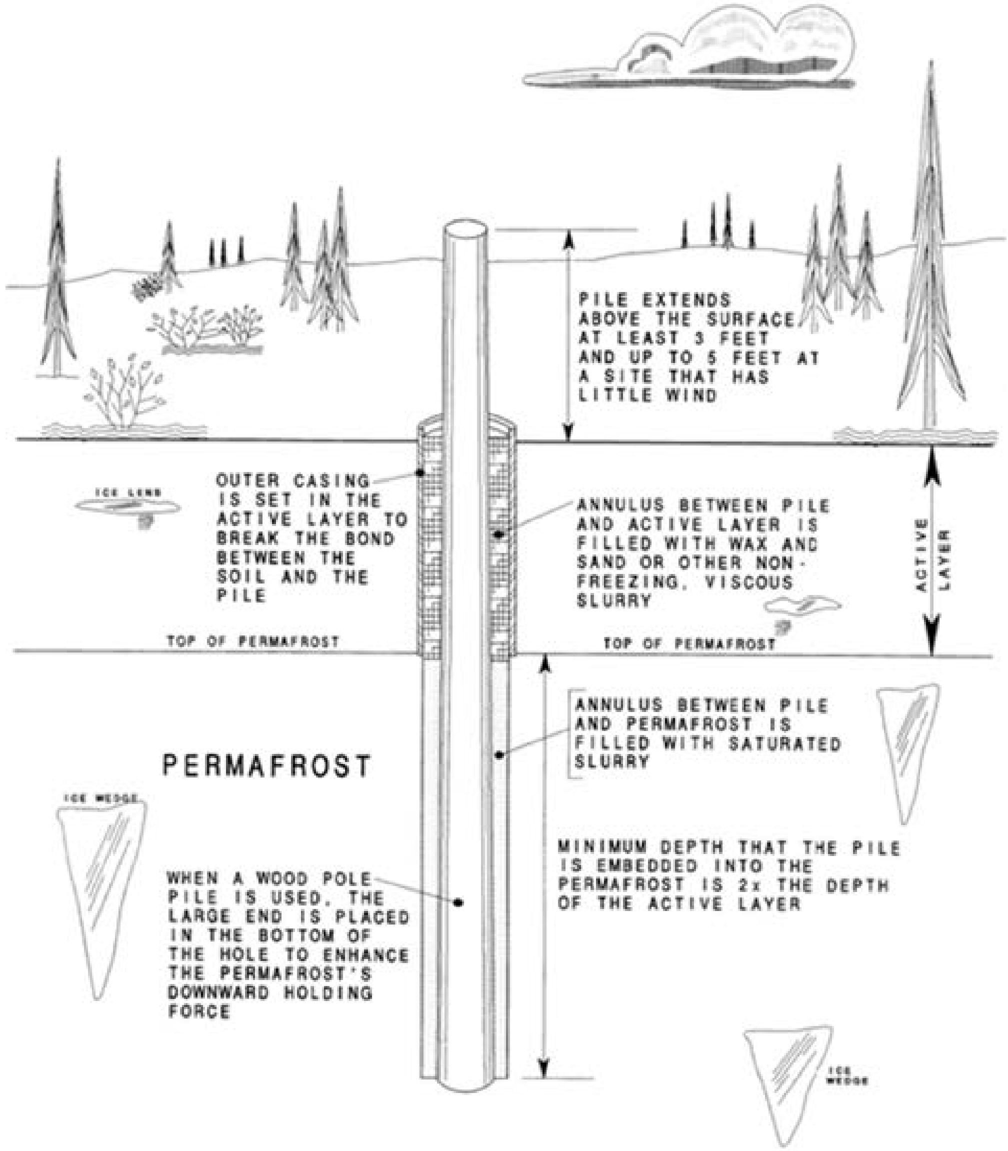


Figure 17. Typical slurried pile installation in permafrost (McFadden 2000)

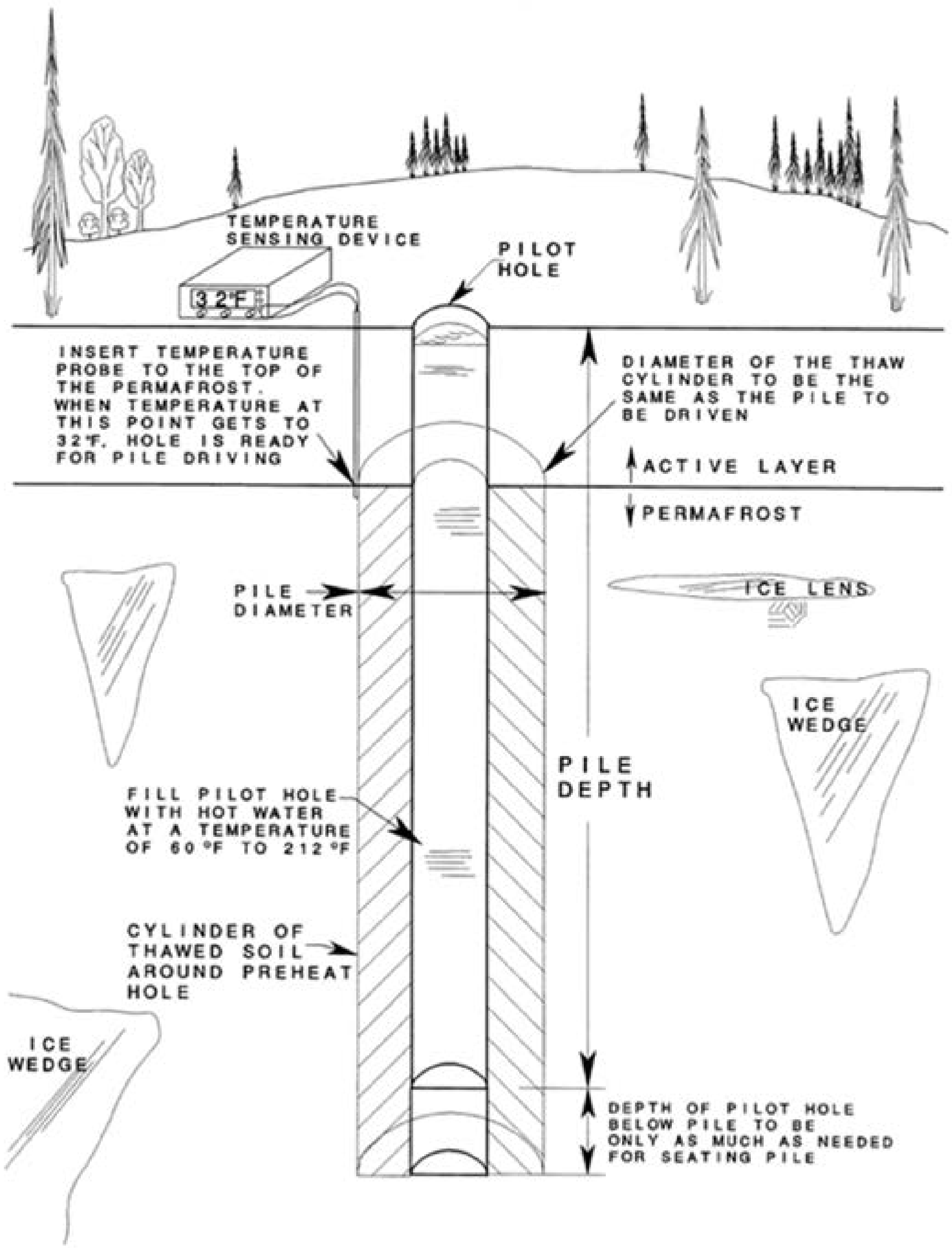


Figure 18. Preparation of pilot hole in preparation for driving a pile permafrost (McFadden 2000)

Shallow Foundation

Shallow foundations are used in permafrost much less than piles. But shallow foundations may be more economical in many cases and could be an acceptable alternative to piles. Figures 19 to 24 illustrate the typical shallow foundations used in permafrost.

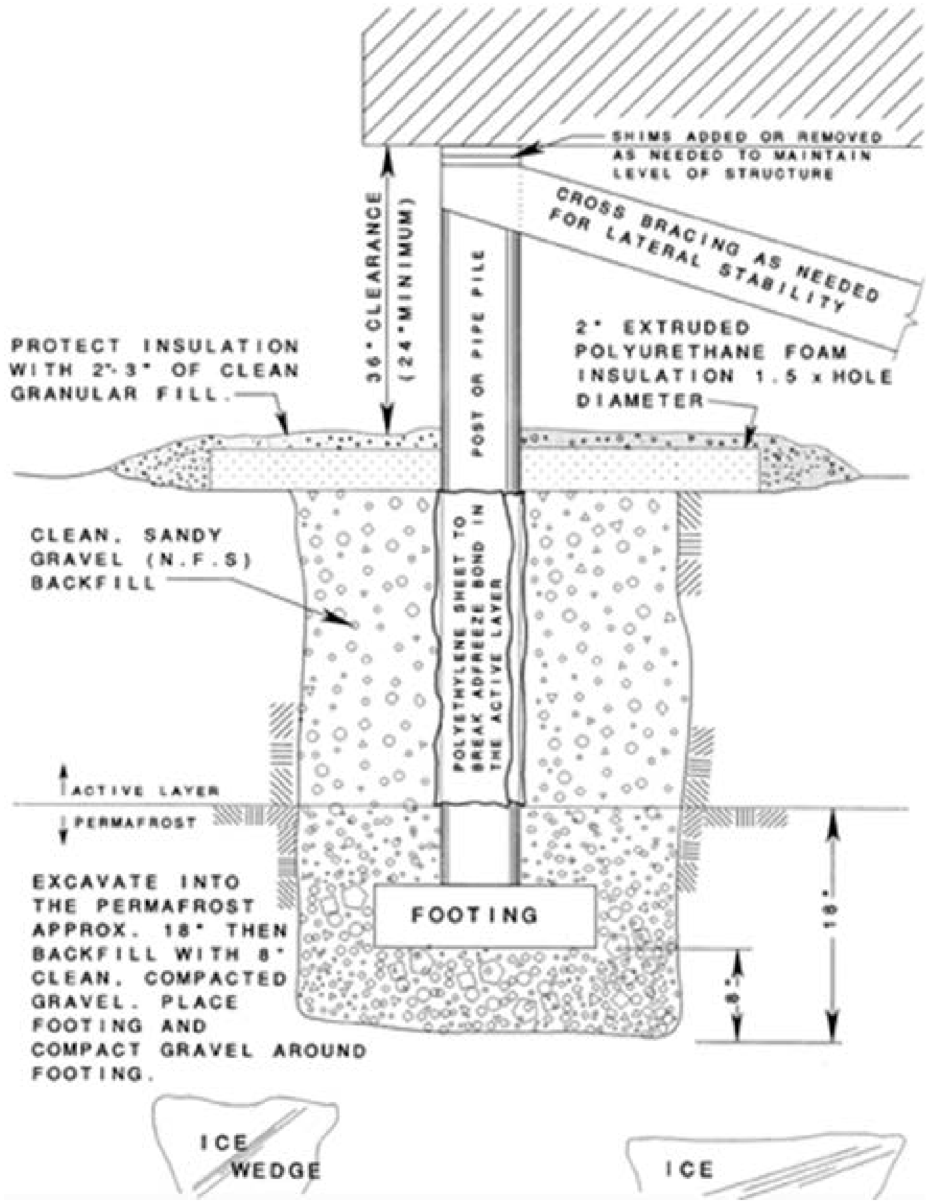


Figure 19. Shallow pile foundation (McFadden 2000)

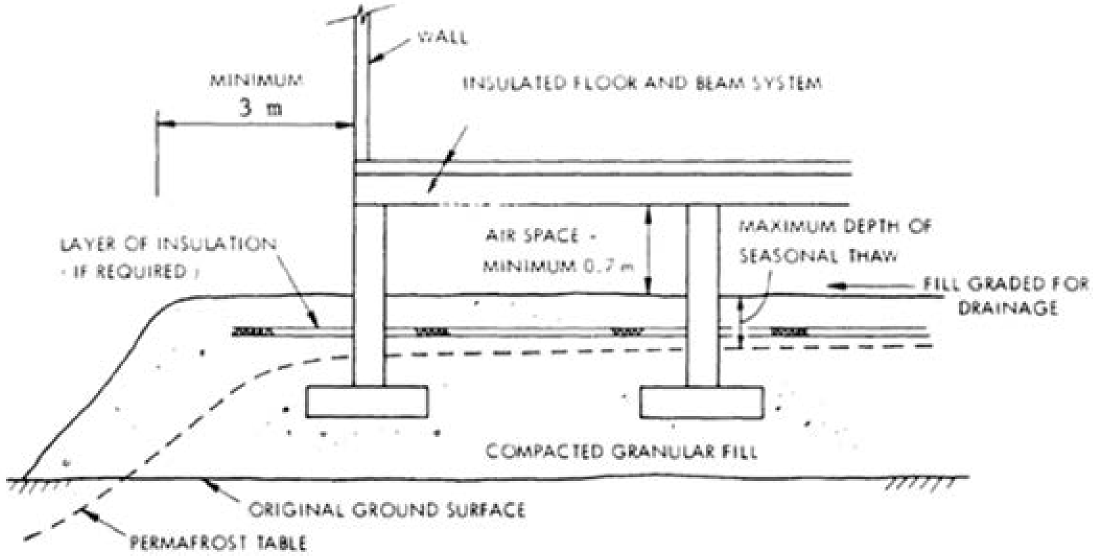


Figure 20. Typical shallow foundation footing in permafrost, embedded in a thick, insulated gravel pad placed on the ground surface (after Johnston 1981)

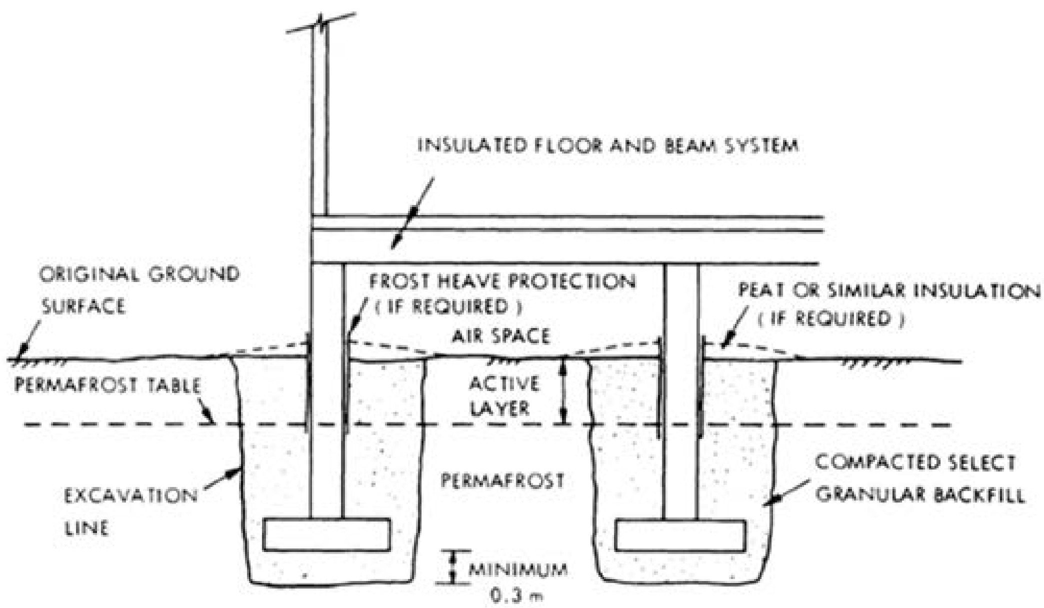


Figure 21. Typical shallow foundation footings in permafrost, placed in backfilled pits excavated below the original ground surface (after Johnston 1981)

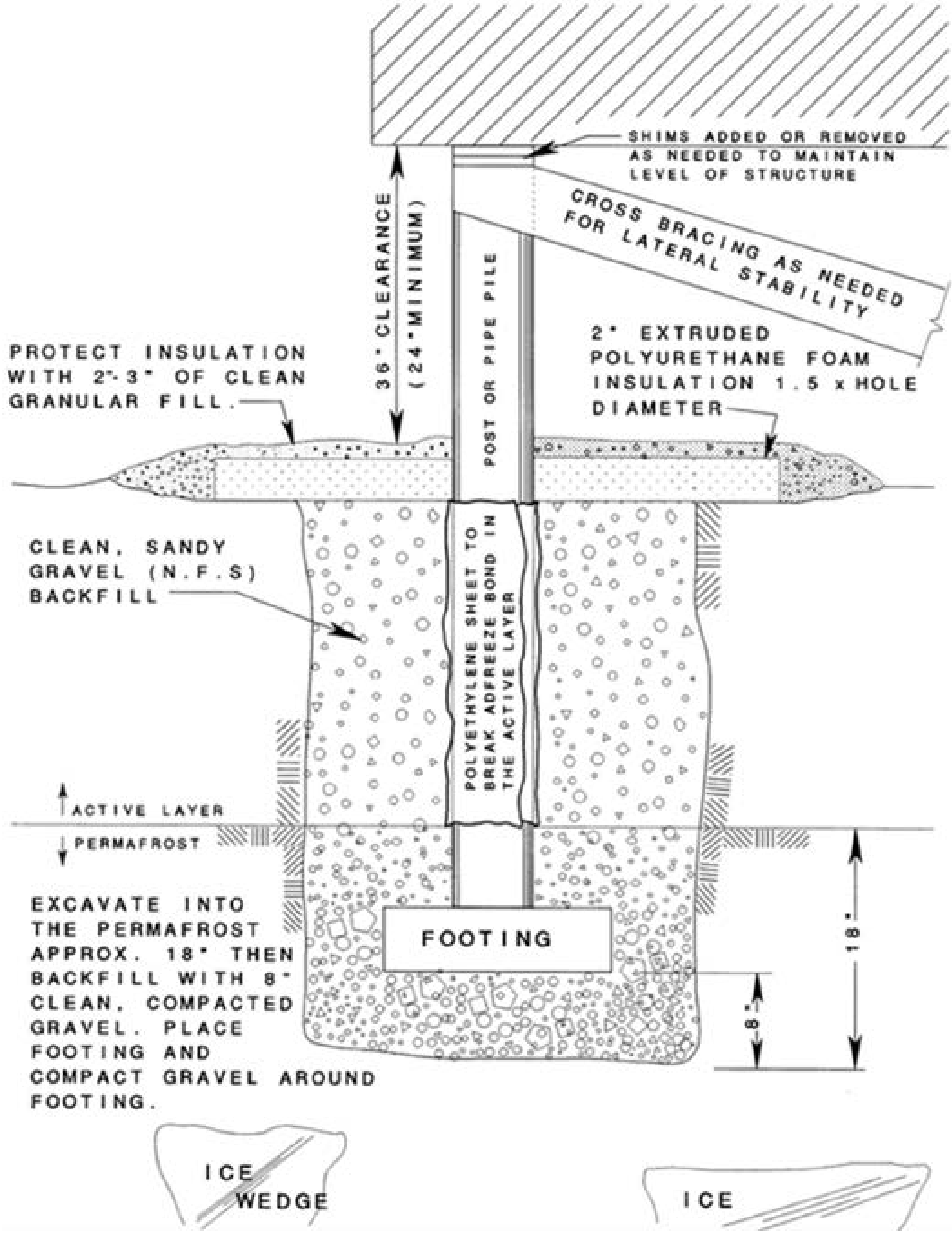


Figure 22. Shallow foundation on permafrost, where neither drilling or driving equipment is available; this method is labor intensive and not as reliable as the deep pile foundations (McFadden 2000)

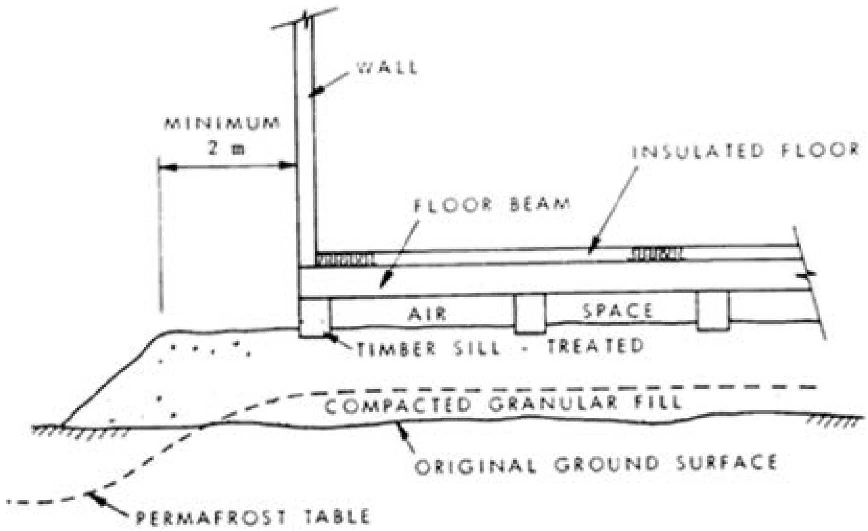


Figure 23. Shallow foundation on permafrost: typical timber sill surface foundation (after Johnston 1981)

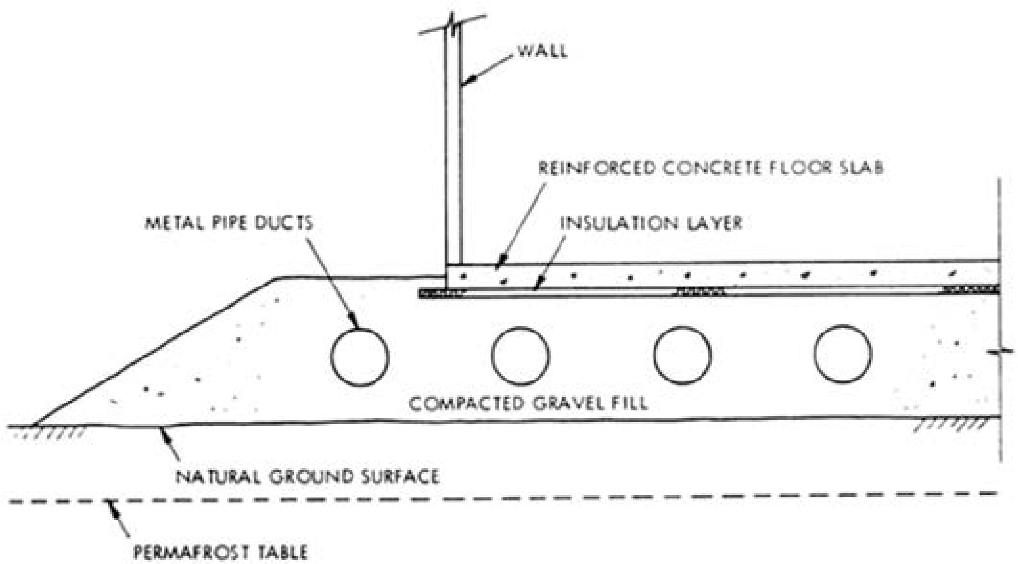


Figure 24. Shallow foundation on permafrost: typical insulated concrete floor slab placed on duct-ventilated compacted fill (after Johnston 1981)

Slab-on-grade construction procedure (McFadden 2001): First, a layer of clean compacted sand of 6 to 8 inch thick should be placed as bedding directly on undisturbed ground surface. Then the ventilation tubes are placed on the clean sand bedding and must be checked to ensure that the tubes are supported along their entire length and that they do not "bridge" any holes or voids. Then, sand should be compacted around the tubes in layers with 3 to 4 inch per layer until the tubes are covered to a depth of about 6 inch. This allows adequate heat transfer between the soil and the pipe. Then, a rigid foam insulation layer of extruded polystyrene (XPS) foam with thickness depending on the region should be placed over the area directly beneath the structure to reduce the heat flow into the frozen soil. Given that for construction in Alaska floor insulation on the order of R-20 to R-40 is needed, assuming the use of XPS with R value of 5 per in. is to be used, insulation thickness ranging from 4 in. to 8 in. would need to be considered, depending on the region. The insulation should then be covered with a layer of clean gravel of 4 to 6 inch in thickness to protect the insulation. Altogether, a minimum of 18 in. to 22 in. (including minimum 4-in. to 8 in. XPS foam) of support should be placed beneath the slab-on-grade.

The configuration of slab-on-grade foundation for a water tank on permafrost is show in Figure 25; bearing pressure on the ice-rich permafrost was assumed to 3200 psf (Miller 1993).

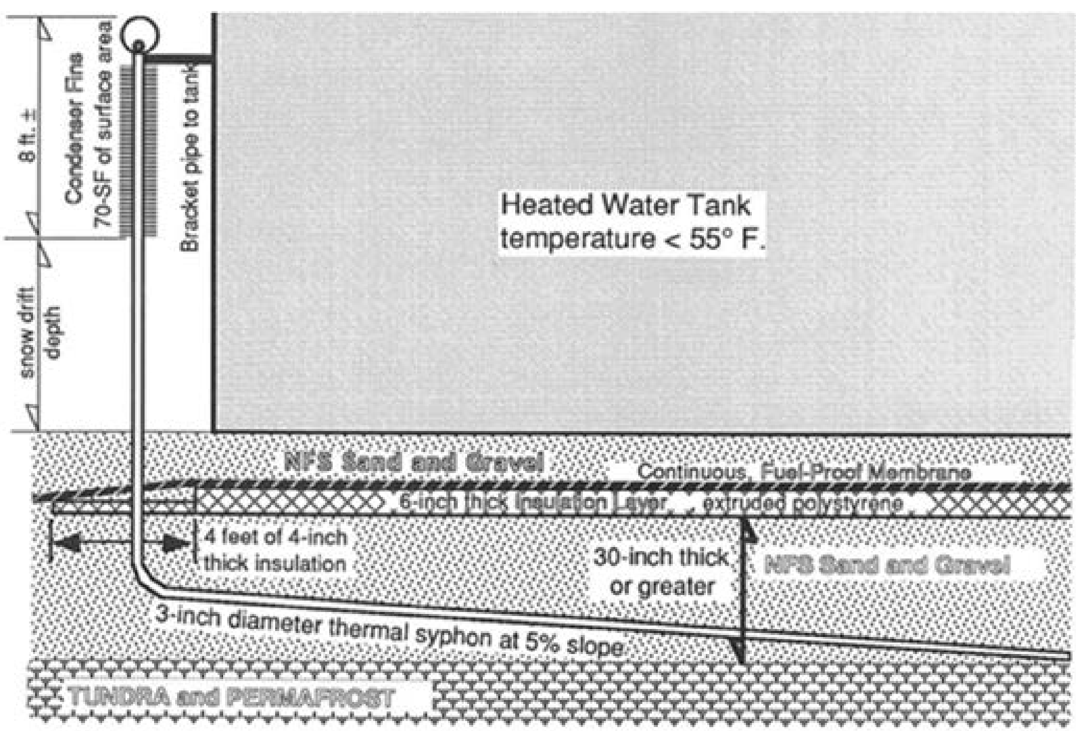


Figure 25. A slab-on-grade foundation on permafrost for a water-tank in Point Lay, Alaska (Miller 1993).

Insulation system

Floor and in-ground insulation should be used to minimize heat losses from heated superstructures and maintain the permafrost table at the desired level. In addition, piers and footing columns should be protected against adfreeze (adhesion to ice) uplift forces due to frost action. For heated, heavily loaded large structures, such as garages, hangars, and oil tanks, an insulated ground-supported slab provided with artificial cooling (as shown in Figure 25) is a preferable solution. Insulation system should be combined with active heat extraction (using thermosyphons) to keep the ground freezing, to maintain adequate bearing capacity and minimize settlement.

Extruded polystyrene (XPS) insulation is widely used in construction in the far north. XPS rigid foam is water resistant and rigid and can maintain thickness under load. XPS should not be in contact with hydrocarbon fuels, which can degrade XPS into a non-insulating gel. As mentioned earlier, assuming an XPS R-value of 5 and a requirement for floor R-value in northern regions of around R-40, a minimum of 8 in, thick XPS would be needed to ensure no heat transfer between the concrete floor and ground surface. Of course, a detailed thermal modeling and analysis will be needed to consider accurate boundary conditions and any thermal bridging that may exist in the actual construction.

A natural convection cooling device is commonly used to keep the ground frozen. Either closed single-phase convection tube (where working fluid transfers heat out of the ground without phase change) or two-phase thermosyphon (where working fluid transfers heat out of the ground with phase change) can be used. The working fluid depends on the recommendation of the contractor who will install the cooling device.

Applicable loads on structure

Structure: Gravity (self-weight need be as light as possible), snow, wind, earthquake, support settlement, temperature

The loads for structural analysis of the finite element model of the habitat will include self-weight of the materials, snow load, wind, and seismic loads. Detailed load calculation based on ASCE 7 will be developed for Model D for the final report. For the current report, conservative approximate loads are used for snow and seismic loads. For the finite element modeling , we have assumed the piles are fixed at the ground level, which is a conservative assumption in the sense that it yields more critical moments in the piles.

Adjustable Jacking Systems

One of the techniques for managing potential permafrost related settlement is to adjust the house elevation at top of the piles in case of the base floor becomes out of level. Current recommended practice is to provide adjustable jacks under floor beams as shown in Figure 26.

Figure 26. Example use of Saddle Bracket jacks over piles to adjust elevation due to soil settlement resulting from thawing effect in active layer and permafrost zone (CCHRC 2014)

The simplest jacking systems are Saddle Brackets (as shown in Figures 26 and 27), referred to as 4 in. Galvanized Adjustable Pier Support Bracket. There is also adjustable floor jacks, e.g., 15 Gauge Floor Jacks, telescoping jack for temporary support, size range 1'-1' 3" (Figure 28). Such adjustable jacks are generally available through Lowe's, Home Depot, and Amazon. Instructions for use of such jacks is provided in the CCHRC document: GalenaConstructionManual.pdf (cchrc.org).

Figure 27. Saddle bracket jack

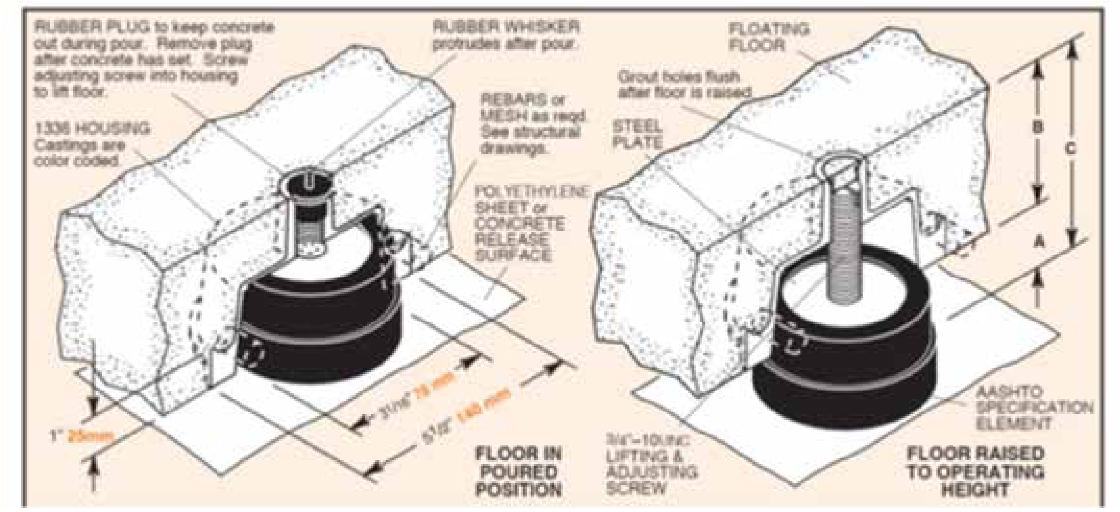
https://www.homedepot.com/p/Mutual-Materials-4-in-Galvanized-Adjustable-Pier-Support-Bracket-595739/100323005

Figure 28. Adjustable floor jacks.

https://www.amazon.com/Tiger-Brand-Jack-Post-JS-15/dp/B001B15DEU/ref=asc_df_B001B15DEU/?tag=hyprod-20&linkCode=df0&hvadid=198091670152&hvpos=&hvnetw=g&hvrand=2829727466628169764&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=1025314&hvtargid=pla-350445345259&psc=1

More complex variety of jacking systems are also available and provided by different vendors such as Mason Industries, Inc., VMC Group, and Kinetics Noise Control, An example is shown in Figure 29 below. These jacks can be used for floating concrete floors.

(a) <https://mason-ind.com/fsn/>

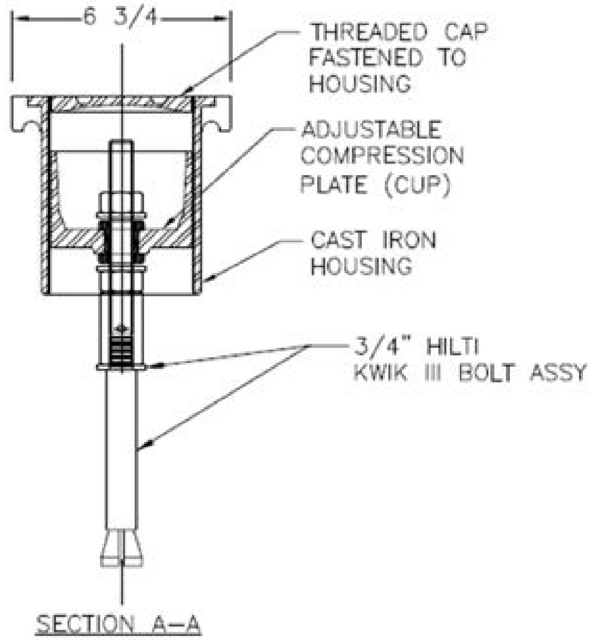


(b) file:///C:/Users/amm7.PSU_ENGINEERING/Downloads/FSN_DS-50-4.pdf

Figure 29. Jack-Up Flooring. Products

The vendor VMC group provides a Jack-up isolator shown in Figure 30 specifically designed for seismic applications and can resist overturning moments of a 1.0g demand level.

(a) <https://www.thevmcgroup.com/catalog/SubCategoryProduct?subCatProdId=129&pscid=0>



(b) https://www.thevmcgroup.com/Frontend/Media/Model%20ASFM%20Seismic%20floor%20restraint.pdf

Figure 30. Jack-Up Isolator For Floating Floors

Furthermore, some seismic isolation systems are also available to minimize the seismic load effect on the structure by isolating the structure from the foundation. Examples of such isolation systems are shown in Figure 31. At this stage, these are only concepts we have identified, but we have not considered these more advance systems in modeling and analysis. These systems could be further studied in Phase 2.

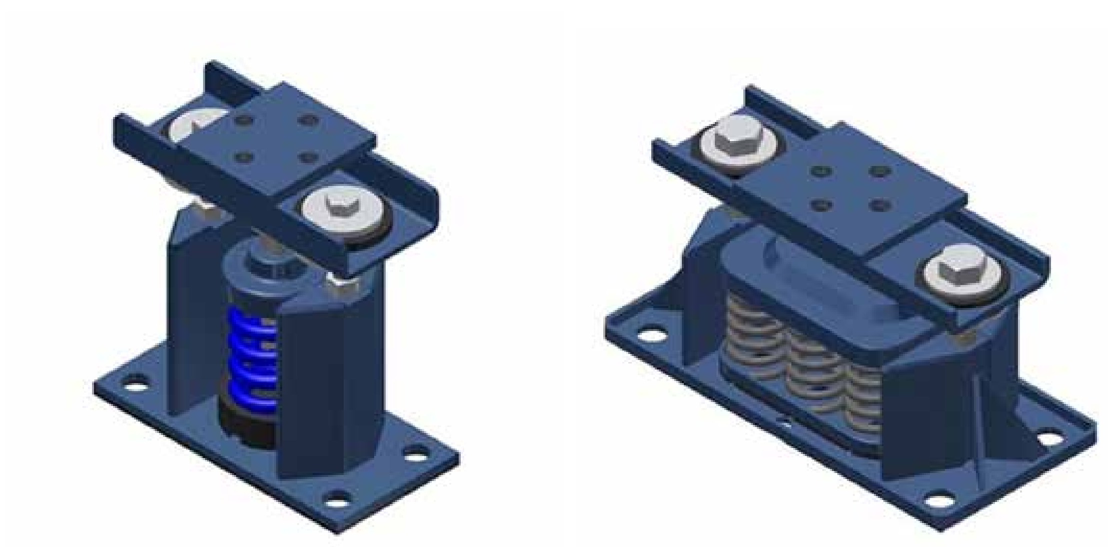
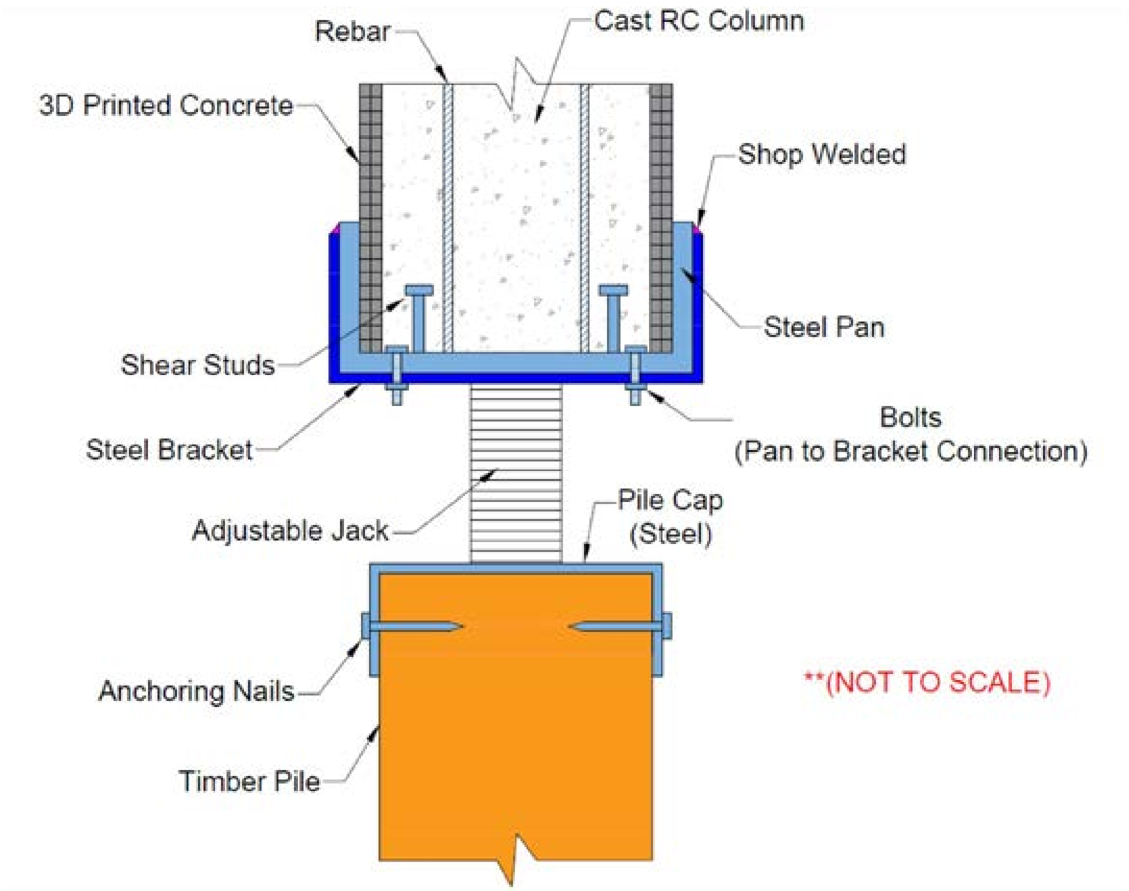
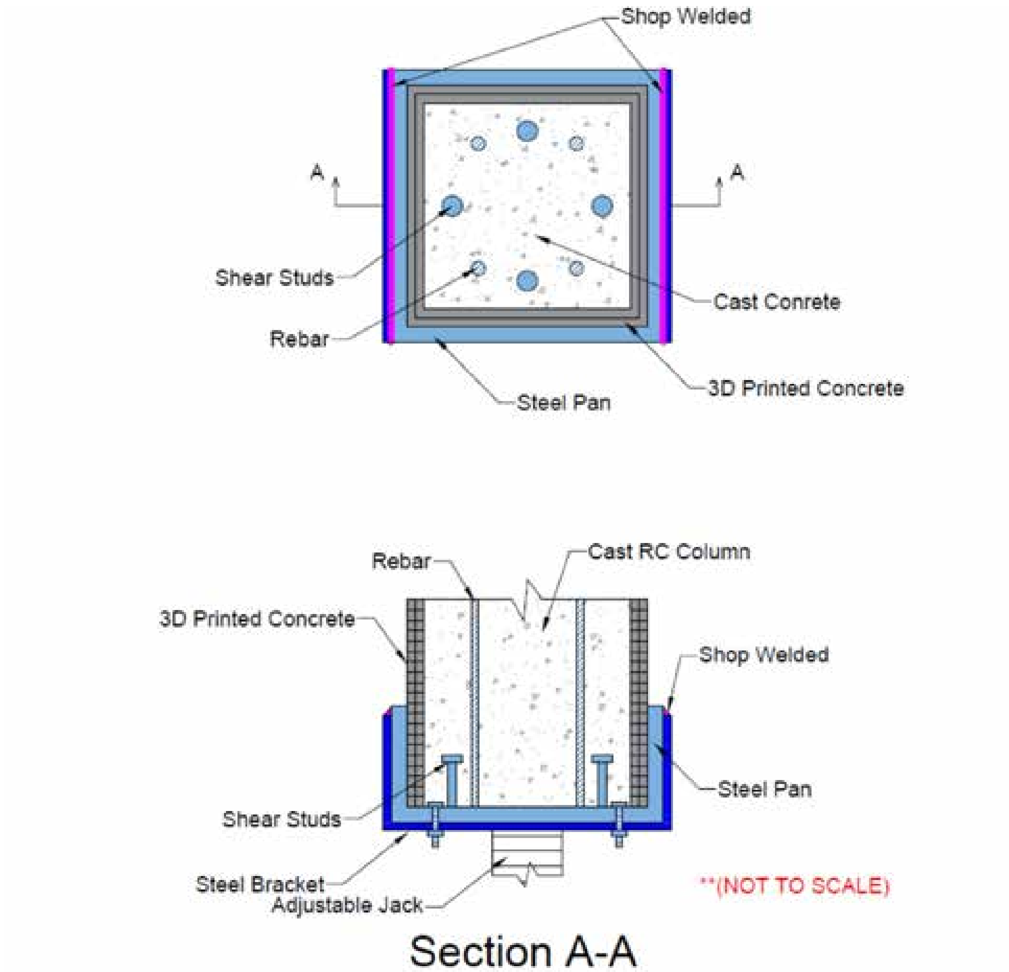


Figure 31. Seismic isolators. https://mason-ind.com/slrso-1%e2%80%b3-def-single-spring/

For this Phase of the study, however, we have considered the more affordable saddle type jacks or adjustable jack to be used between top of piles and bottom of columns as conceptually illustrated in the Figure 32. A more detailed version of the concept is considered and described in the finite element modeling sections for capacity calculation.



(a) Pile to printed column connection through adjustable jack



(b) Conceptual detail for anchoring printed reinforced concrete column to adjustable jack

Figure 32. Conceptual design of printed column to wooden pile connection through adjustable jack.

Material Properties (Concrete, Reinforcement, Soil, Insulation

The concrete properties are developed in this study based on mixture designs provided, as explained subsequently. For this report, we use existing information about concrete properties until specific material properties are developed. Currently, GCT concrete material properties are considered for modeling.

Reinforcement to use consists of fiber reinforcement in the concrete mixture and steel rebar reinforcement in critical areas such as columns.

Software and Modeling

In this Phase 1 final report, both Models B and D are analyzed in detail using finite element modeling software Abaqus. Initially Model D is discussed, as it is the more preferred model. The structure of Model D consists of (bottom up) a) timber piles fixed at the bottom and pinned at the top (through a hinge mechanism), b) concrete columns arching at the top to merge with the slab, c) bottom concrete slab, d) concrete wall, e) vault structure with closed top. On the other hand, Model B has the same structure, except for the top that can have a slab or glass window to close the top. Sections below describe the modeling and analysis in detail.

An initial assessment of the structural performance of both Solution D and Solution B is provided in sections that follow. It should be noted that a more advanced analysis including structural performance "during printing", which is a crucial part of the design, will be developed in the second phase of the project toward printing a prototype structure. The analysis presented here serves as a proof-of-concept of the safety of this habitat for a varied range of loads, considering dead load, snow load, wind load, and earthquake effect. Finite element analysis of the two structure models was performed in Abaqus to evaluate the structural behavior of the conceptual habitat structures. Both solutions D and B were modeled assuming a wall and shell thickness of 7 inches (18 centimeters).

Structural Analysis of Model D – Finite Element Analysis

Material Properties

As a starting note, Abaqus has no built-in system of units, which means that a structure should be modeled with consistent units, such as described in the Abaqus manual (Table 3). For this project we will be working in feet (ft) as the base unit.

Table 3. Consistent units – Abaqus.

Quantity	SI	SI (mm)	US Unit (ft)	US Unit (inch)
Length	m	mm	ft	in
Force	N	N	lbf	lbf
Mass	kg	tonne (10^3 kg)	slug	lbf s^2/in
Time	s	s	s	s
Stress	Pa (N/m^2)	MPa (N/mm^2)	lbf/ft^2	psi (lbf/in^2)
Energy	J	mJ (10^{-3} J)	ft lbf	in lbf
Density	kg/m^3	tonne/mm^3	slug/ft^3	lbf s^2/in^4

This structure was modeled using timber for the piles, with a 2 feet length above ground (below ground length is not considered for the analysis, as the pile is assumed fixed at the ground surface), and concrete for the superstructure, which includes the vaulted grounding and the wall-shell system. Information regarding material properties for both timber and concrete can be found respectively in Tables 4 and 5. For concrete, a compressive strength of 2500 psi was adopted, and damage plasticity constitutive model as the one described in Hafezolghorani et al. (2017) was applied to study the behavior in a non-elastic way, and a density of 4.66 slug/ft^3 (150lb/ft^3) was used. Both concrete and timber sections were inserted as solid homogeneous materials (Figure 33a).

Table 4. Timber properties - Abaqus.

Density (slug/ft^3)		1.40
Elastic Properties	Young's Modulus (lb/ft^2)	3.34E+08
Elastic Properties	Poisson's ratio	0.43

Table 5. Concrete Properties – Abaqus.

Concrete Elasticity		Plasticity parameters	
Young's Modulus lb/ft^2	2.88E+08	Dilatation Angle (º)	31
		Eccentricity	0.1
		fb0/fc0	1.16
Poisson's ratio	0.20	K	0.67
		Viscosity parameter	0
Concrete compressive behavior		**Concrete compression damage**	
Yield stress lb/ft^2	**Inelastic strain**	**Damage parameter C**	**Inelastic strain**
213031.39	0	0	0
267333.50	7.73585E-05	0	7.73585E-05
313281.45	0.000173585	0	0.000173585
350875.22	0.000288679	0	0.000288679
380114.83	0.000422642	0	0.000422642
401000.26	0.000575472	0	0.000575472
413531.51	0.00074717	0	0.00074717
417708.60	0.000937736	0	0.000937736
413531.51	0.00114717	0.01	0.00114717
401000.26	0.001375472	0.04	0.001375472
380114.83	0.001622642	0.09	0.001622642
350875.22	0.001888679	0.16	0.001888679
313281.45	0.002173585	0.25	0.002173585
267333.50	0.002477358	0.36	0.002477358
213031.39	0.0028	0.49	0.0028
150375.10	0.003141509	0.64	0.003141509
79364.63	0.003501887	0.81	0.003501887
Concrete tensile behavior		**Concrete tension damage**	
Yield stress lb/ft2	**Cracking strain**	**Damage parameter T**	**Inelastic strain**
41770.86	0	0	0
417.7086	0.000943396	0.99	0.000943396

Boundary Conditions

To model the boundary condition of the piles at the ground surface, we assume piles are fixed, which with the assumption of frozen ground is a reasonable conservative assumption for modeling. However, the adjustable jack system that would be located between top of each pile and bottom of printed concrete column will be assumed to act as a frictionless pin and modeled using pinned conditions. Therefore, pinned conditions were assigned to the bottom of each column, or base of the vaulted grounding in grey color (Figure 32b). It should be pointed out that at this stage, we conservatively assume there is one such adjustable jack under each concrete column. For a more refined evaluation and minimizing the cost, we will study the need for a jack under each column, and if justified, we can place such jacks under selected columns.

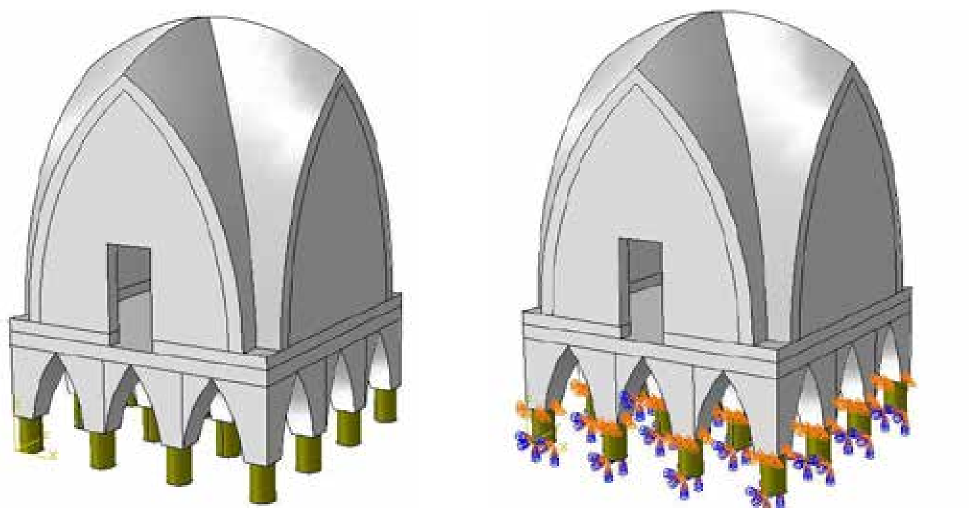


Figure 33. (a) Model and respective materials; (b) Boundary conditions assigned to the model: (i) fixed at the bottom of piles (brown); (ii) pinned at the bottom of the grounding columns (grey).

Loading

Four types of loads are considered in the load combinations for this analysis, namely, self-weight, snow, seismic and wind load. The respective load combinations are presented below, where D stands for Deadload, S for snow, E for Earthquake load, and W for Wind load.

- $0.9D+1.0E$ (Seismic)
- $1.2D+1.0W$ (Wind)
- $1.2D+1.6S+0.5W$ (Snow)

Seismic Load Calculations, E

For the quantification of seismic loads, since there is the possibility of building in a remote area in the state of Alaska, a conservative approach of considering the region with largest ground acceleration was taken, which would be in the surrounding area of Valdez.

Since we will be dealing with a structural system that has no steel rebar reinforcement in the main body of the structure, and only in the cast concrete part of the columns, we conservatively assume the structure has no ductility, and that the response will be expected to be mostly elastic, which led us to adopt an R (response amplification factor) value of 1.0. In addition, we assume a risk category of II, and site class category D. The remaining seismic parameters are presented in Table 6.

Table 6. Seismic parameters.

Risk Category	II
Site class Category	D
S_S (g)	2
S_1 (g)	1
T_L (s)	6
F_a	1
F_v	1.7

S_{MS} (g)	2
S_{M1} (g)	1.7
S_{DS} (g)	1.333
S_{D1} (g)	1.133
I_e (importance factor)	1
R (response amplification factor)	1

From the Abaqus model, the fundamental period of the structure was found to be 0.0218 seconds, which is an indicator of a very stiff system, validating the argument to use R equal to 1.0. Finally, the Seismic Response coefficient (C_s) can be determined from Equation (1).

$$C_s = S_{DS} / \left(R / I_e \right) = 1.333 \tag{1}$$

The value for Cs is between the lower and upper limits values that are, respectively, defined in Equation (2) and (3) from ASCE 7-16 (ASCE 2016), which in this case would be respectively 0.0587 and 51.97.

$$C_{s,min} = 0.044 S_{DS} I_e \tag{2}$$

$$C_{s,max} = S_{D1} / T \left(R / I_e \right) \tag{3}$$

For this initial assessment of the seismic loads, since there are no irregularities, and the height of the structure is lower than 160ft, we adopt the Equivalent Lateral Force Method, which requires the determination of the base shear. The equivalent lateral force method serves as a simplified method to replace dynamic load effects by an equivalent static distributed lateral load at each floor of a building, which serves the purpose at this stage of the project.

The only step left to determine the base shear is the evaluation of the seismic weight, which in this case corresponds to the weight of the structure. The weight is obtained from the product of the volume with the density of concrete, resulting in a weight of 82,870 lbf, or 82.87 kips. The base shear is then calculated using Equation (4).

$$Base\ shear = C_s * Seismic\ Weight = 1.333 * 82.87^k = 110.49^k$$

For the Abaqus modeling, the horizontal forces are applied at two levels (Figure 34), namely: (i) the slab above the grounding, with a force of 23.32 kips, which would be reflected upon an applied pressure of 3239 psf; (ii) the Shell + Wall system, with a force of 87.17 kips. The quantification of the described forces is shown in Table 7, and the application in the model in Figure 34.

Table 7. Equivalent Lateral force method results for Model D.

Level	h_i (ft)	h (ft)	w_i (kips)	$w*h^k$	C_{VX}	F_i (kips)	Area of application (ft^2)	Pressure (psf)
Shell + Walls	10	15	45.97	689.51	0.79	87.17	15.03	5799
Slab	5	5	36.90	184.50	0.21	23.32	7.20	3239
		Total	82.87	874	1	110.49		
		Base shear	110.49					

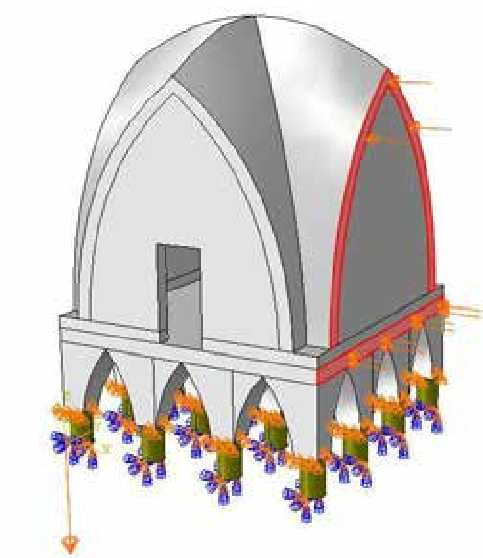


Figure 34. Seismic load combination, with gravity load, and seismic load applied as pressure to the slab, and to part of the face of the wall.

Wind Load Calculations, W

Wind Load Parameters

For the wind load calculation, the largest basic wind speed (*V*) of 150 mph in the Alaska region was adopted conservatively. In addition, the house is assumed to be in a flat, unobstructed area, including unbroken ice, corresponding to Exposure Category D. For the gust effect factor, since the fundamental period is 0.0218 seconds, the fundamental frequency is much larger than 1 Hz. Therefore, the building is considered rigid for wind calculation and the gust factor (G) is assumed to be 0.85.

Velocity Pressure, q_z and q_h

Since the height above ground is smaller than 15ft, and exposure category is D, the velocity pressure coefficients K_z and K_h are both equal to 1.03 (ASCE7-16). These coefficients are used to determine the velocity pressure coefficients q_z and q_h (Equation 4 and 5), which leads to the forces applied on the house. The wind directionality factor, K_d, and the topographic factor, K_{zt}, were assumed to be respectively 0.85 and 1.0.

$$q_z = 0.00256 K_z K_{zt} K_d V^2 = 50.43\ psf \tag{4}$$

$$q_h = 0.00256 K_h K_{zt} K_d V^2 = 50.43\ psf \tag{5}$$

Wind Loads

The remaining parameter to calculate wind loads is the pressure coefficient, C_p, which is equal to 0.8 for the windward wall, or the wall the directly receives wind, and -0.5 for the leeward wall, or the opposite wall to the windward wall. Having calculated the velocity pressure, gust factor, we can determine the wind load for the windward and leeward walls (Equation 6).

$$q_z G C_p = 34.30\ psf$$
$$q_h G C_p = -20.17\ psf \tag{6}$$

Wind Load Scenarios

Load scenarios for wind can be summarized into fours types (Figure 35), where two of those consider torsion effects. In Abaqus, the torsion effect was introduced by applying an equivalent pressure load in opposite faces (see Figure 36).

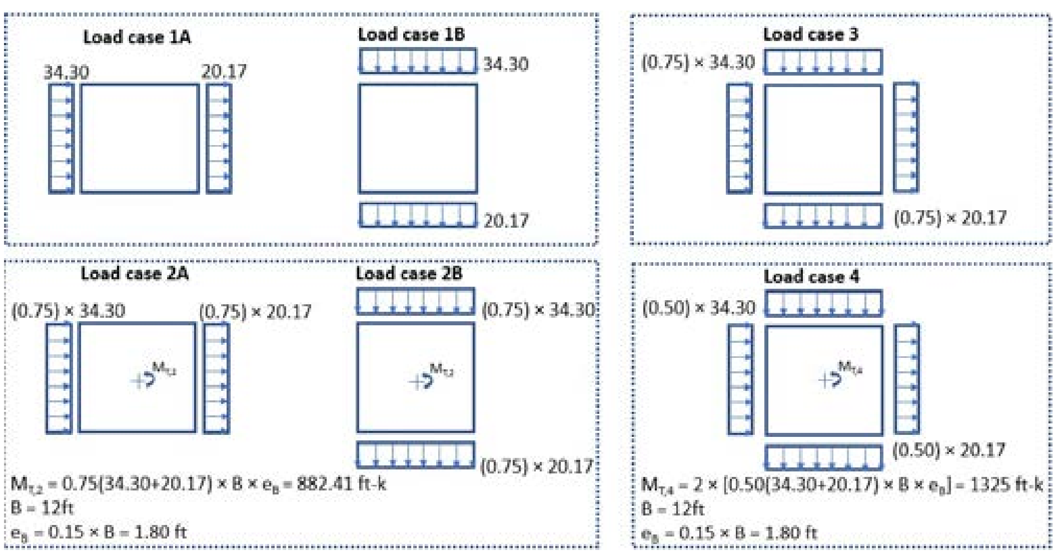


Figure 35. Wind load scenarios (top view).

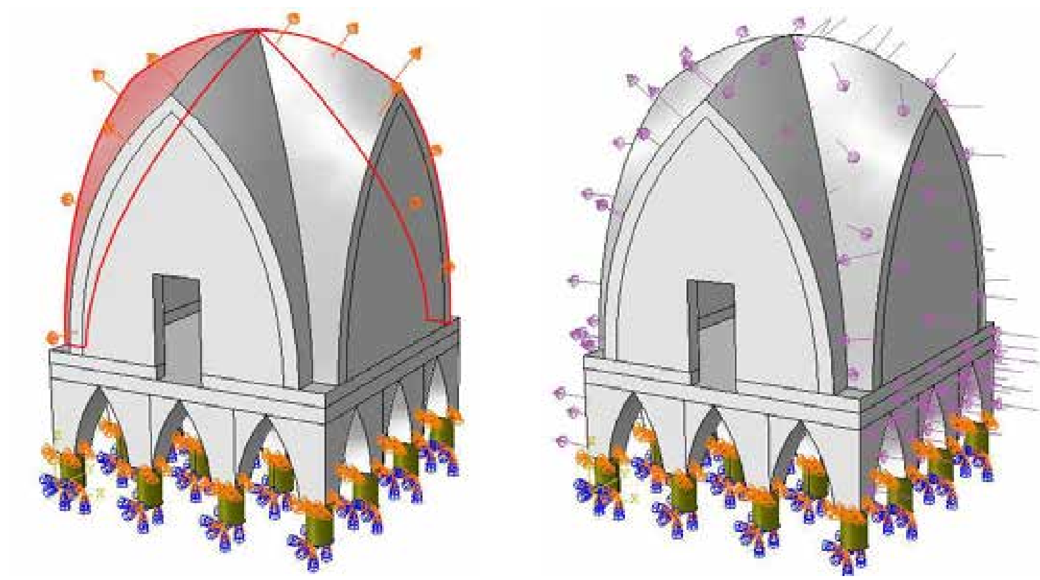


Figure 36. (a) Equivalent torsional pressure applied in the house for Load case 2 and 4; (b) Load case 1A representation.

Snow Load Calculations, S

Snow loads should be an expected load in the design of roofing systems and should be assumed to act on the horizontal projection of the surface in question. In the case of both model D or model B (respectively a pointed cross-vault, and a pointed cloister vault sliced around 70% of its height), we have a roof that is geometrically defined from a pointed barrel vault. According to ASCE 7-16, barrel vault roofs shall have a slope factor, C_s, equal to 1.0 (Section 7.4.4 ASCE7-16). As a result, the sloped roof balanced snow load, p_s, is equal to:

$$p_s = C_s p_f = p_f = 0.7 C_e C_t I_s p_g = 86.24\ psf \quad (7)$$

Where,

- c_e is the exposure factor, which is 0.70 in Alaska.
- c_t is the thermal factor, which is 1.1 in structures kept just above freezing
- I_s is the importance factor, and equal to 1.0
- p_g is the ground snow load, which is equal 160 psf in Valdez, Alaska.

Due to the large inclination of roof, which is close the 70 degrees along its height, there is no need to calculate unbalanced roof loads (Section 7.6.2. of ASCE7-16) due to the influence wind loads on the snow distribution on the roof.

The application of roof loads is presented in Figure 37 (a), which shows the projection of the load on the surfaces of interest. The load scenario in Abaqus for snow load combination, includes deadload, and 0.5 times wind load (Figure 37 (b)), which in this case involved the wind load case 3 (see Figure 35 that consists of loads in both windward and leeward walls, since it controls wind load design for the columns.

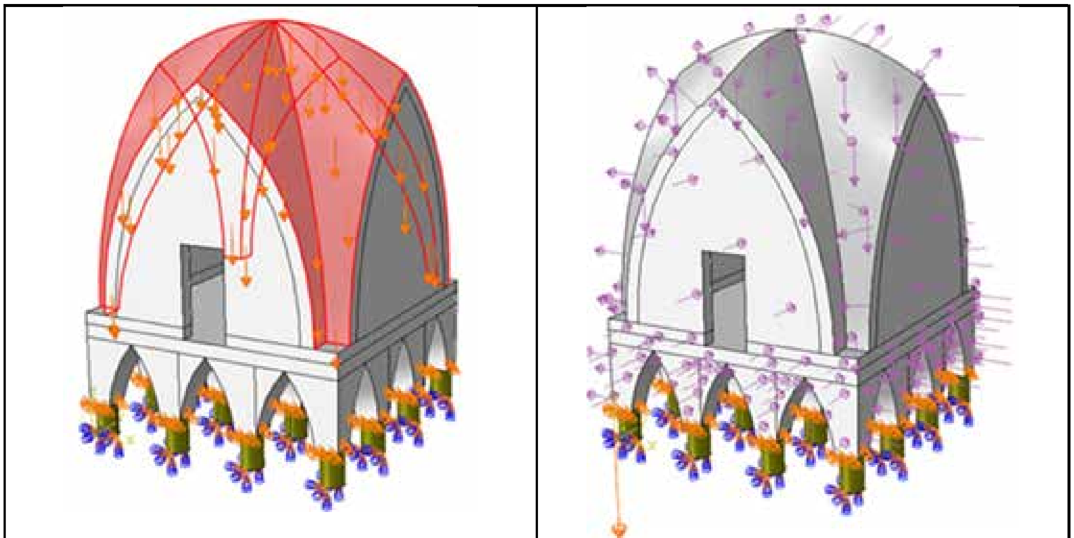


Figure 37. (a) Snow loads on house; (b) Snow load combination to analyze in Abaqus, which includes deadload and wind load case 3.

Meshing

For this stage, a coarser mesh with 0.7ft size elements was adopted, and as a result of the complex geometry of the concrete shell and vaulted grounding, 10-node quadratic tetrahedral elements (C3D10 – Figure 38(a)), which has 4 integration points, was chosen for the simulation. The meshing is present in Figure 38(b).

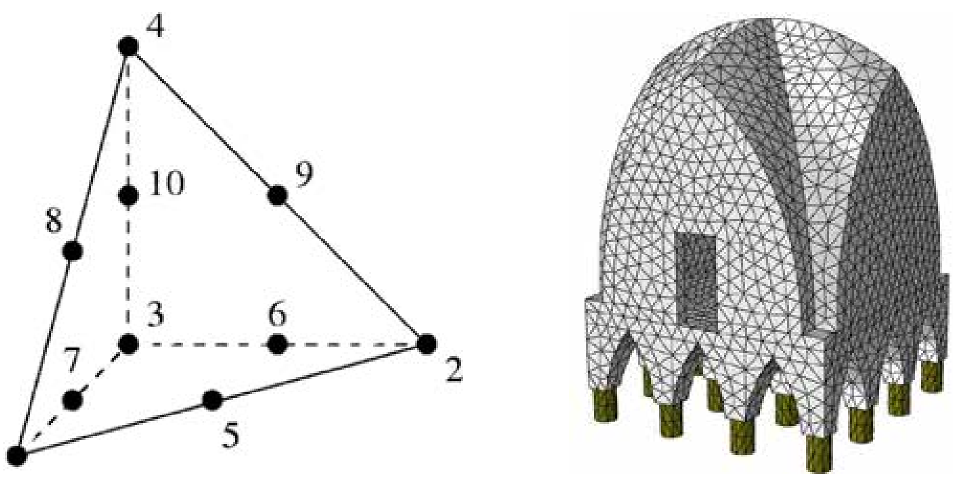


Figure 38. (a) 10-node tetrahedral element (C3D10); (b) Mesh for analysis.

Results

Seismic Load Case: 0.9D + 1.0E

Starting with the seismic load case, the maximum displacement obtained from the model was 1.332E-03 feet, or 0.016 inches (Figure 39). However, for this structure, the set of elements that could represent more problems would be the grounding columns, namely the base, where the cross-section is smaller, which will provide most of the system's flexibility. This is showcased by the Von Mises stress diagram that shows a stress concentration in that region (Figure 40).

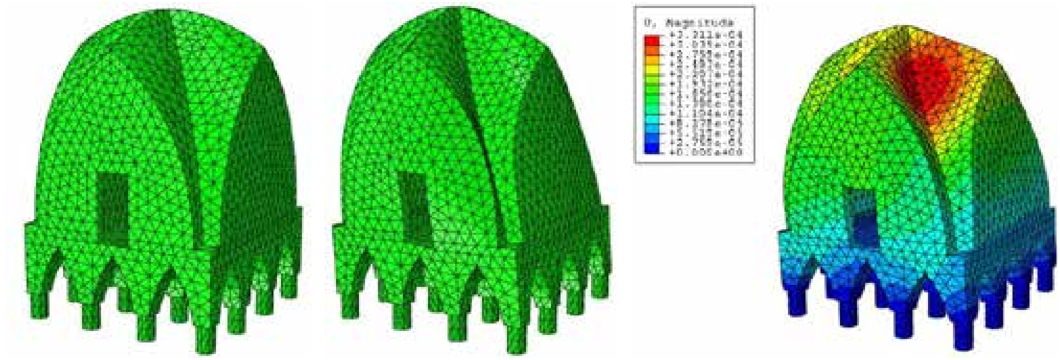


Figure 39. (a) Meshed structure; (b) Deformation under seismic load; (c) Displacement field in the structure (Deformation scale factor: 1.339E3).

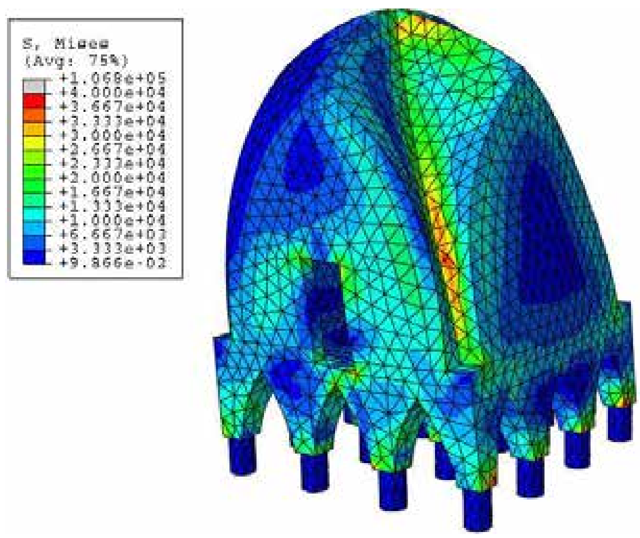


Figure 40: Von Mises stress field (lb/ft^2), showing larger stresses on the bottom of columns and region between walls.

To evaluate and design at the base of the columns, we want to work with stress resultants, such as forces and moments, which is also provided by Abaqus by performing section cut at the desirable height, which in this case is the base of the columns. The force and moment components at the level of the base of the grounding columns are presented respectively in Figures 41 and 42. The gravity load (F_z) corresponds to approximately 0.9 times the weight of the structure (0.9 * 82,870lb = 74,583 lb), whose difference is due to vertical load caused by overturning effect of the seismic loading on the grounding columns. The Fx force of around 93.77 kips, which is mainly from the Equivalent lateral forces, will control the shear design of the columns. Three columns were identified as having the larger difference in the results as far as the forces and moments are concerned, which will serve as the representative elements of the analysis.

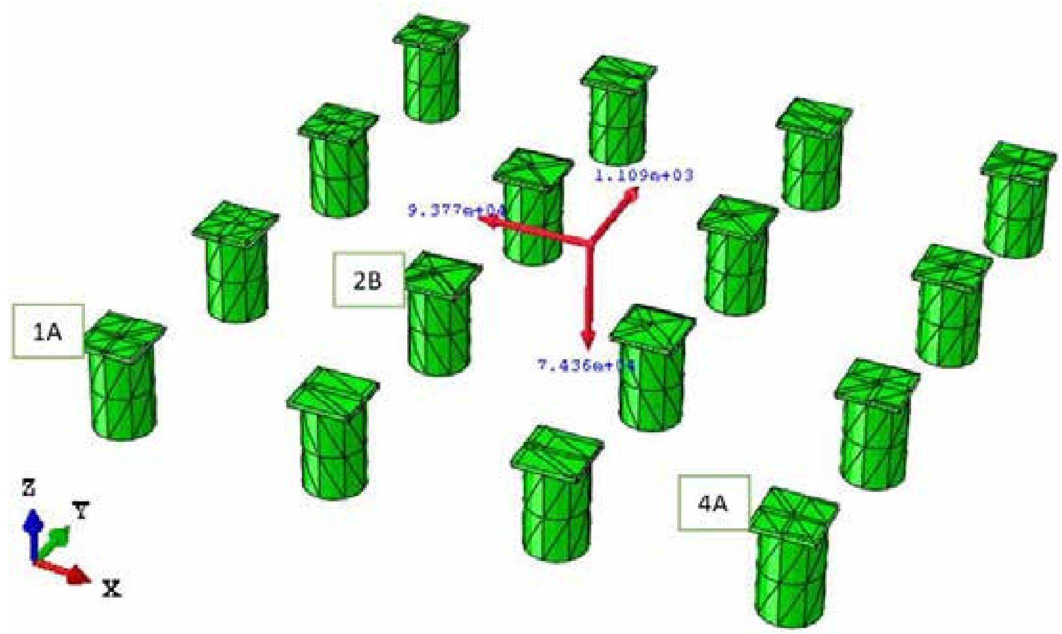


Figure 41: Force components (in lbf) at column base level for Seismic loading (0.9D+1.0Ex).

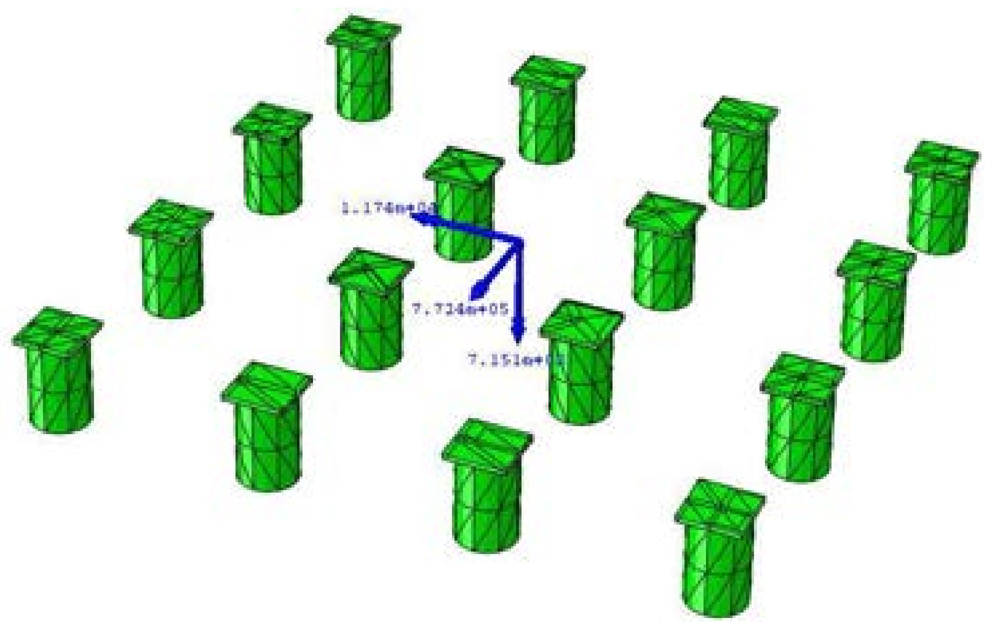


Figure 42. Moment components (lbf-ft) at column base level for Seismic loading (0.9D+1.0Ex).

The force (shear in two orthogonal horizontal directions and axial force) and moment components for columns 2B, 1A, and 4A are, respectively, presented in Figure 43 to 45. The first observation is that as expected, exterior columns have considerably more axial load than the interior columns, and this can be explained by two reasons: first, the overturning effect of the equivalent seismic load in the building results in vertical forces, which will be maximum in compression in alignment 1, and maximum in tension in alignment 4; secondly, the shell and wall system is placed on the perimeter of the structure, which results in the perimeter columns sustaining most of its weight. The second observation is that the columns in alignment 4, such as the case of column 4A, are under tension, which is explained by the fact that the tensile force from the overturning effect of the equivalent seismic horizontal forces were larger than the compressive force that resulted from the deadload. As a result, the connection of the columns in alignment 4 should be designed to have enough pullout strength. Third, interior columns are subjected to larger shear forces, which is a result of having a larger tributary area, which leads to larger stiffness in the system interior column-grounding, thus absorbing more percentage of the lateral forces. Finally, moments are very small ($M_{x,max}$ = 4.591 ft-k) which is due to assigning pinned connections to the base of the columns. A summary of the forces and moments is shown in Table 8.

Figure 43. Force and Moment components for base of interior Column 2B under seismic loading.

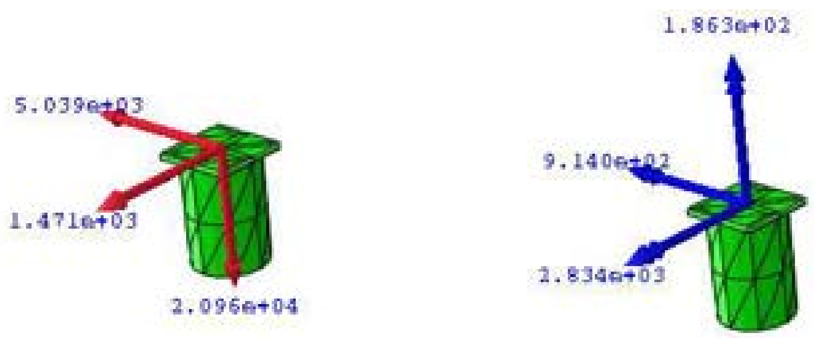


Figure 44. Force and Moment components for base of exterior Column 1A under seismic loading.

Figure 45. Force and Moment components for base of exterior Column 4A under seismic loading.

Wind Load Case: 1.2 + 1.0W

As previously described, four load cases for the wind action were considered in Abaqus, where two of those cases include an applied torsion effect (cases 2 and 4). Information regarding the displacement field, forces, and moments at the base of the columns for all different cases can be found subsequently. The main takeaway from this analysis is that cases 1 and 3 result in higher shear at the base of the columns. Column 1A will be considered for the analysis since it experiences the larger shear force. The next step consists of verifying the satisfactory performance of the column and connection to the adjustable jack under the applied forces, which can be illustrated by evaluating the capacities vs. the demands.

Snow Load Case: 1.2D + 1.6S + 0.5W

The results for the snow load combination are presented in the section on Additional Finite Element analysis Results, where a maximum displacement of 3.107E-04 feet was obtained close to the top of the roof, as expected. Since the wind load is applied at half of the value, a lower shear was obtained in comparison with the other load combinations. It can be concluded that the snow combination does not control the design of the columns.

Column and Connection Design

The analysis described in the previous section allowed the determination of the forces and moments in the columns of interest. A summary of the forces and moments used to evaluate the safety and, if needed, to redesign the members, is in Table 8. With this information, it will be possible to verify the column for shear capacity, and design the needed reinforcement in the columns, and determine if the connection between column and adjustable jack is adequate.

Table 8. Forces and Moments for interest columns in Model D.

	Column		Forces and Moments				
	Column		Forces and Moments				
Load combination	Designation	Type of Column	N (k)	V_x (k)	V_y (k)	M_x (ft-k)	M_y (ft-k)
Seismic: 0.9D+1.0E	2B	Interior	4.00	8.57	0.05	0.08	4.59
	1A	Exterior	20.96	5.04	1.47	0.91	2.83
	4A	Exterior	-13.76	4.72	0.04	1.37	3.74
Wind Load 1: 1.2D+1.0W	1A	Exterior	14.51	1.82	1.40	0.26	0.15
Wind Load 3: 1.2D+1.0W	1A	Exterior	13.10	1.68	1.03	0.46	0.17
Snow: 1.2D+1.6S+0.5W	1A	Exterior	11.18	1.32	0.94	0.32	0.04

Shear capacity check for base of columns and reinforcement solution

The shear capacity can be calculated conservatively by using expression (22.5.5.1) from ACI318-14, which would be valid for non-prestressed members without (conservatively) axial force, where V_c is the shear strength, f_c' the compressive strength of concrete, and *b* and *a* are the dimensions of the section. For this scenario, we are only (conservatively) considering the cast concrete area, whose dimension would be the difference of 14.4 inches (1.2ft) with 3 beads of printed of concrete on each side, resulting in an area of 7.32 x 7.32 inches.

$$V_c = 2\sqrt{f_c'}ba = 2 * \sqrt{2500} * 7.32 * 7.32 = 5358\ lb = 5.358\ k \quad (8)$$

The shear capacity of 5.36k is not enough for the Column 2B in the case of the seismic load, whose shear force is equal to 8.57k. To check this criterion, the section should be upsized to 16.5 inches, which will provide a cast concrete area of 9.40x9.40 inches. This way, the new shear capacity will be enough to withstand shear from the seismic load case.

$$V_{c,upsized} = 2\sqrt{f_c'}ba = 2 * \sqrt{2500} * 9.40 * 9.40 = 8836\ lb = 8.836\ k \quad (9)$$

In terms of reinforcement solution, a shear reinforcement solution of No.3 @ 6 inches will be adopted to create the rebar cage to be placed within the printed shell of the column and along the height of the columns, while 4 No. 5 rebars will be used as longitudinal column reinforcement, which will work as a minimum reinforcement, since the moments are approximately zero at the bottom of the columns. A detail of the cross-section of the base of the column, including reinforcement is present in Figure 46.

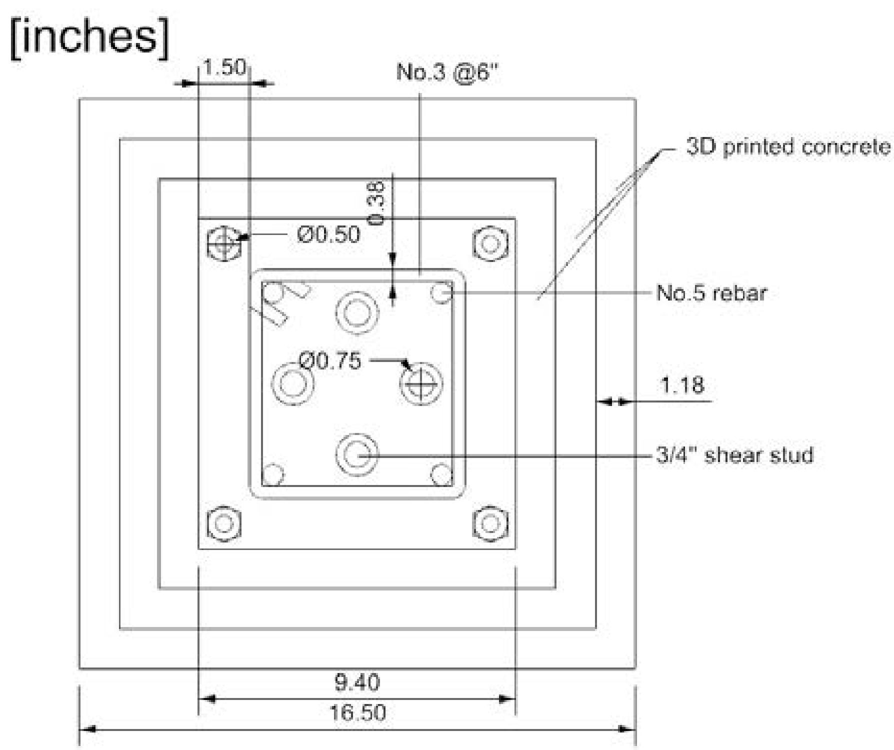


Figure 46. Cross-section detail for the base of the column.

Shear Stud Design

In the current design, shear studs are used to connect concrete to serve as a way to propagate loads to the saddle jack bracket. The main verification for the shear stud is usually nominal strength in terms of shear. However, in the seismic load scenario, the columns in alignment 4 end up being under tension, which require an additional check concerning pullout strength of the studs.

Nominal shear strength of single steel stud, Q_n

The value of the nominal shear strength of single steel stud is given in *Specification* Section I8.2a of AISC, and is defined in Equation (10), where, A_{sa} is the cross-sectional area of the shank of the stud, R_g and R_p are reduction factors to account for experimental test results, which are considered as equal to 1.0, and Fu is the minimum specified tensile strength of the stud. A ¾'' stud will be considered at this stage.

$$Q_n = 0.5A_{sa}\sqrt{f_c'E_c} \leq R_gR_pA_{sa}F_u \tag{10}$$

$$<=> 0.5 * 0.4417 * \sqrt{2.5 * 2880} = 18.35k \leq 1 * 1 * 0.4417 * 65 = 28.71k$$

The nominal shear strength of each shear stud is equal to 18.35 kips, which provides enough strength for the shear demand, since the largest shear in a column will be column 2B for the seismic load scenario which has 8.57 kips distributed by 4 studs, corresponding to 2.142 kips, which is substantially lower than the value obtained in Equation (10).

Pullout strength, N_{pn}

In the case of an excessive tensile force in a concrete column, the anchoring shear stud may tend to pull out, but because the stud head, it tend to break a cone out of the concrete as its failure mode. In particular, under combined shear and the tensile force in concrete column resulting from earthquake, cracking of concrete occurs, which may lead to even lower resistance against the pullout of the shear stud. To estimate pullout strength, ACI318-08 establishes an expression that depends on the shear stud head bearing area, or A_{brg}, compressive strength of concrete, and a pullout cracking modification factor, $\psi_{c,p}$ (Equation 11). A ¾'' stud has head bearing diameter of 1.25'', resulting in an area of 1.23 in^2, and a pullout modificatory factor equal to 1.0 if the concrete is conservatively assumed as cracked.

$$N_{pn} = 8A_{brg}f_c' \, \psi_{c,p} = 24.60k \; (per\ stud) \tag{11}$$

This pullout strength is enough to sustain the tensile load of 3.44 kips (or 13.76/4) kips in each stud of column 4A under seismic load.

Bolt Connecting Saddle Bracket and Steel Pan

In order to assure load transmission from the steel pan to the saddle bracket jack, four bolts will be distributed around the base of the column. At this stage, let us assume a ½''A307 bolt of 60ksi steel. This element will be subjected to combined tension and shear in the columns from alignment 4 when subjected to seismic loads. The quantification of combined shear-tension is obtained from AISC and involves the calculation of a modified tensile stress, F_{nt}' that includes effects of shearing stress (Equation 12).

$$F'_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\varphi F_{nv}} f_{rv} \leq F_{nt} \tag{12}$$

Where F_{nt} is the nominal tensile stress when only tension occurs, F_{nv} is the nominal shear stress when only shear stress occurs, and φ is equal to 0.75 for LRFD. For a ½''A307 bolt, F_{nt} is equal to 45 ksi, F_{nv} is 27 ksi, and f_{rv} is equal to $1.18^k/0.196in^2$, which leads to a F_{nt}' value of 45.12 ksi. Since it must be lower than F_{nt}, we will adopt $F_{nt}' = F_{nt}$ =45 ksi.

Following the calculation of the modified tensile stress, we can obtain the modified tensile strength, R_n.

$$R_n = F'_n A_b = 45 * 0.196 = 8.84k\ (per\ bolt) > \frac{N}{4} = \frac{13.76k}{4} = 3.44k\ (per\ bolt) \tag{13}$$

This confirms that a solution with 4 bolts of ½'' diameter and 65 ksi steel strength assures safety of the connection.

Adjustment Screw Design

The adjustable screw will be subjected to the total axial and shear load from the corresponding column. Therefore, a similar verification to the one performed for the bolt can be made for the adjustable screw. In the case of column 4A, a tensile force of 13.76kips, and shear force of 4.717 kips should be resisted by the adjustable screw.

Assuming a 1.5'' bolt of Grade 8.8, F_{nt} and F_{nv} will be respectively equal to 90ksi and 54ksi, thus resulting in F_{nt}' value of 111.07ksi, which surpasses 90ksi. Therefore, 90ksi will be used as the value of F_{nt}'. Finally, the modified tensile strength, R_n, is obtained from the product of 90ksi with the area of the shank of the 1.5'' bolt, resulting in a strength of 159 kips, which significantly exceeds the axial force of 13.76 kips transmitted to the adjustable screw.

Finally, a complete detail of the connection detail and column is shown in Figure 47.

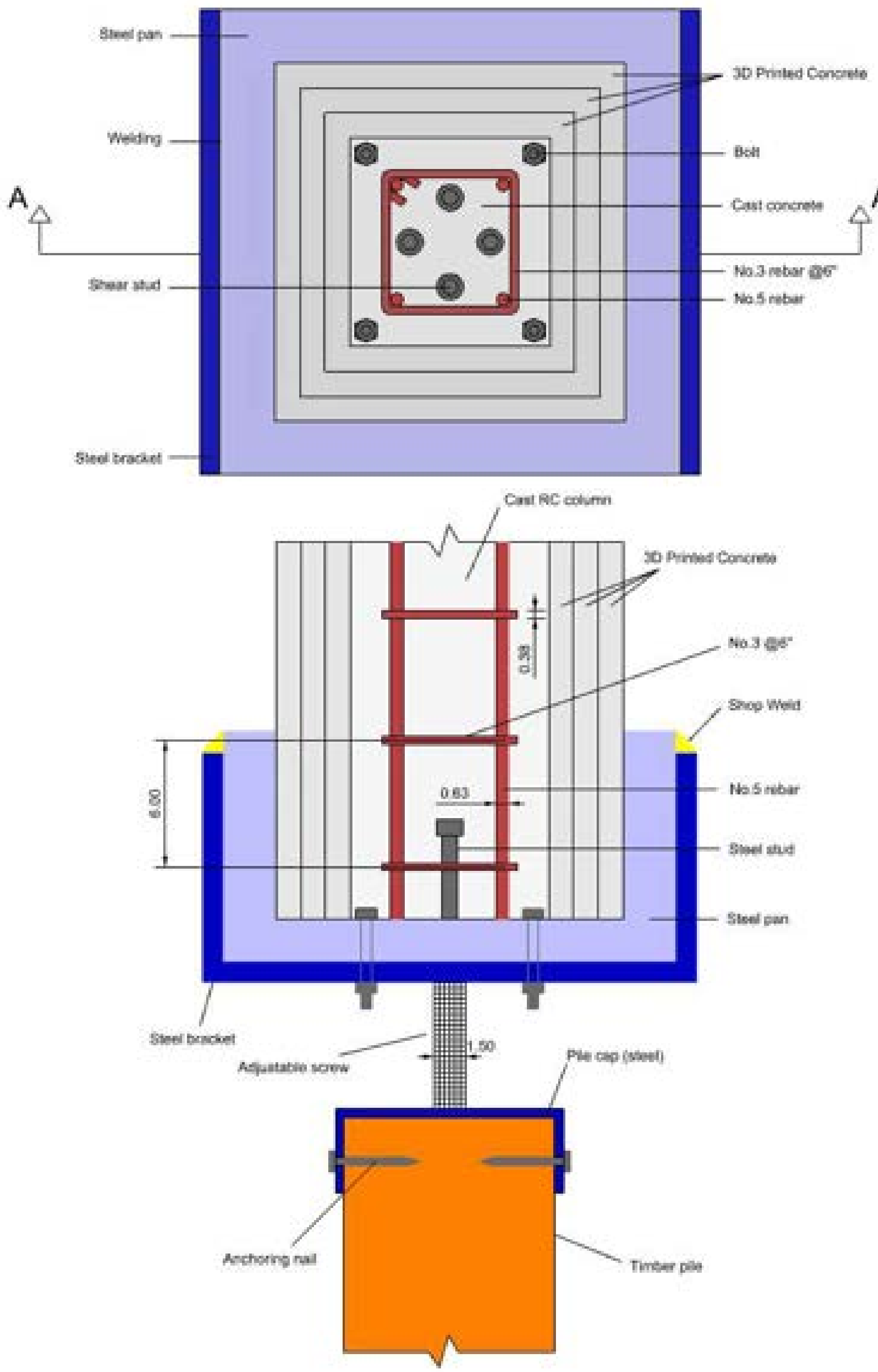


Figure 47. Cross-section and connection detail for the base of the column.

Structural Analysis of Model B – Finite Element Analysis

General Aspects of Modeling

Model B is another solution that is different in terms of roofing system, which consists of a cloister vault, instead of a cross-vault like the one in Model D. The structural analysis in Abaqus follows the same boundary conditions with fixed support for the piles at the ground surface and pinned at the bottom of the printed concrete columns connected to the jacking mechanism.

Loading

Since for model D seismic load case controlled design, we will only analyze model B at this stage for seismic loading.

- 0.9*D*+1.0*E* (Seismic)

Seismic Load Calculation, E

Since we are using the same assumptions for this model, seismic parameters such the Response Amplification factor, SDS, SD1, and Cs remain the same. The difference occurs for the natural period, which is 0.014 seconds, and the seismic weight, which is 69.30 kips, leading to a base shear of 92.17 kips, which will be distributed at the roof level and the floor slab level, that is the load will be distributed over the side of the slab and the side of the roof (see Table 9), as seen in Figure 48.

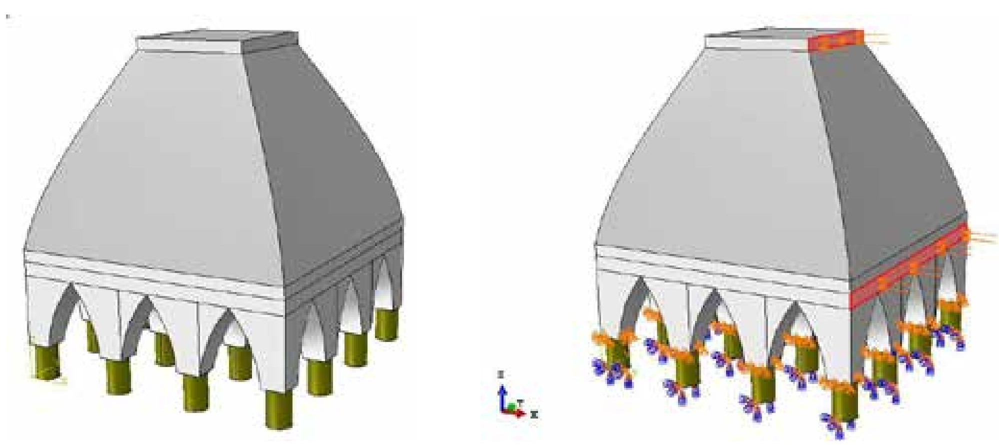


Figure 48. Boundary conditions and Seismic load combination for model B.

Table 9. Equivalent Lateral force method results for Model B.

Level	h_i (ft)	h (ft)	w_i (k)	$w*h^k$	C_{VX}	F_i (kips)	Area (ft2)	Pressure (psf)	Pressure application

Level	h_i (ft)	h (ft)	w_i (kips)	$w*h^k$	C_{vx}	F_i (kips)	Area (ft2)	Pressure (psf)
Shell	10	15	17.33	259.88	0.50	46.20	4.32	10694.44
Slab	5	5	51.98	259.88	0.50	46.20	7.20	6416.67
		S	69.30	520	1	92.40		
		Base shear	92.40					

The maximum displacement (Figure 49) obtained was 7.061E-4 feet, which is smaller than in the case of Model D, which is explained by a more compact and stiff structure, which is also explained by its lower natural frequency. The forces and moments at the base of column level for columns 1A, 2B, and 4A are presented in the Figure 50-52. The same observation regarding columns under tension in alignment 4 can be made, and larger shear in interior columns. Nonetheless, the forces for model B are lower than the ones in Model D, which lead to the conclusion that by designing for model D, by using the same reinforcement solution and upsizing the column base section to 16.5 ft x 16.5 ft, the structure will be safe.

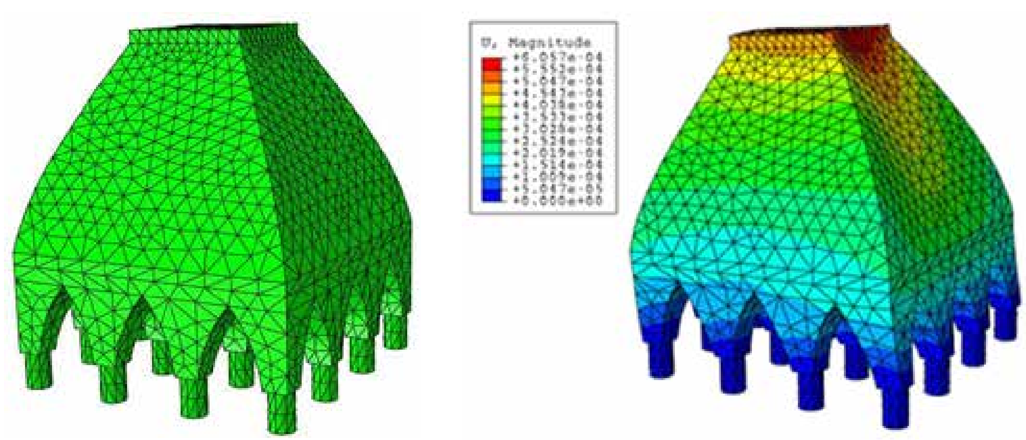


Figure 49. (a) Adopted mesh for Model B, and (b) Displacement field results for seismic loads.

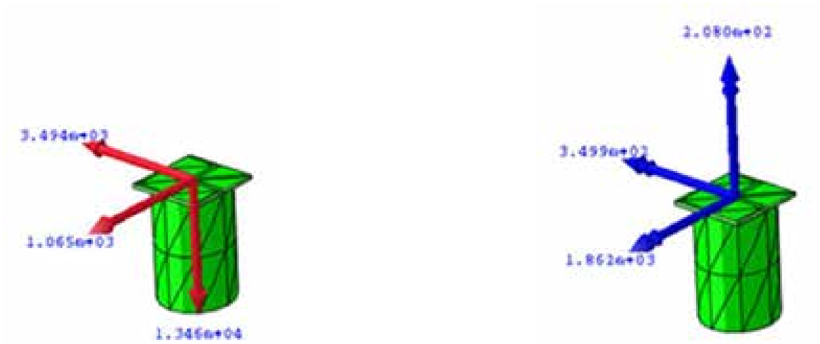


Figure 50. Force and Moment components for base of interior Column 1A under seismic loading.

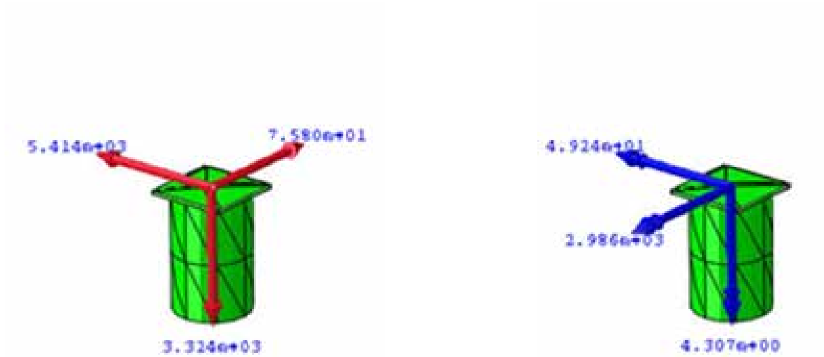


Figure 51. Force and Moment components for base of interior Column 2B under seismic loading.

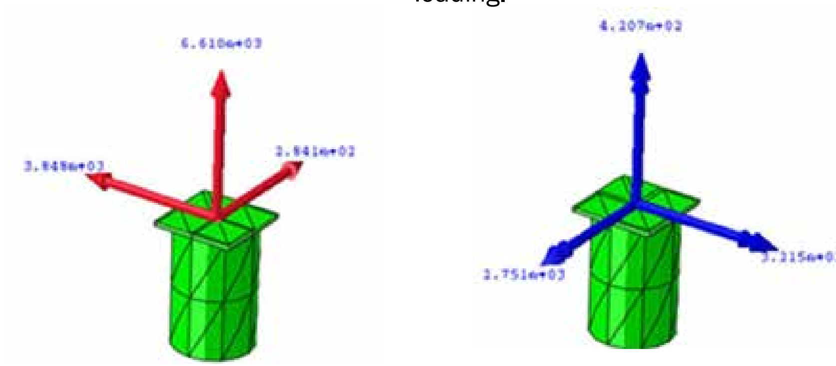


Figure 52. Force and Moment components for base of interior Column 4A under seismic loading.

Table 10. Forces and Moments for interest columns in Model B for seismic load.

	Column		Forces and Moments				
Load combination	Designation	Type of Column	N (k)	V_x (k)	V_y (k)	M_x (ft-k)	M_y (ft-k)
Seismic: 0.9D+1.0E	1A	Exterior	13.46	3.49	1.07	0.35	1.86
	2B	Interior	3.32	5.41	0.08	0.05	2.99
	4A	Exterior	-6.61	3.85	0.28	0.32	2.75

Additional Finite Element Analysis Results

A. Displacement field for load wind loads combinations for Model D

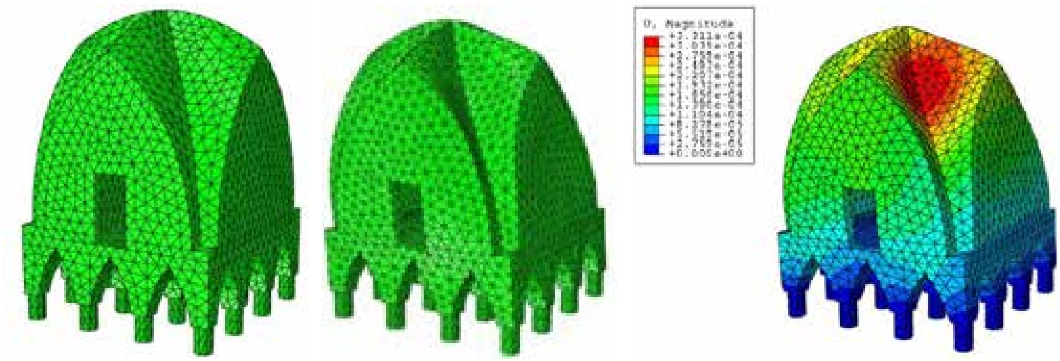


Figure 53. Wind load combination 1 (Deformation scale factor: 6.723E+3).

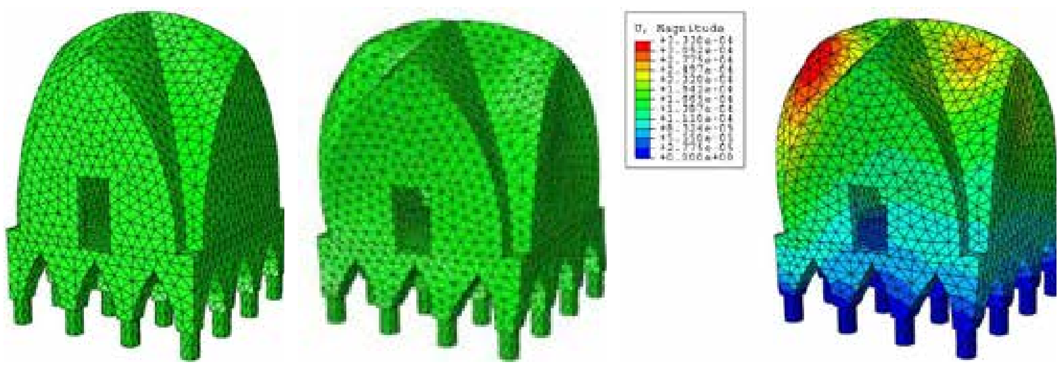


Figure 54. Wind load combination 2: Torsional effect included (Deformation scale factor: 6.110E+3).

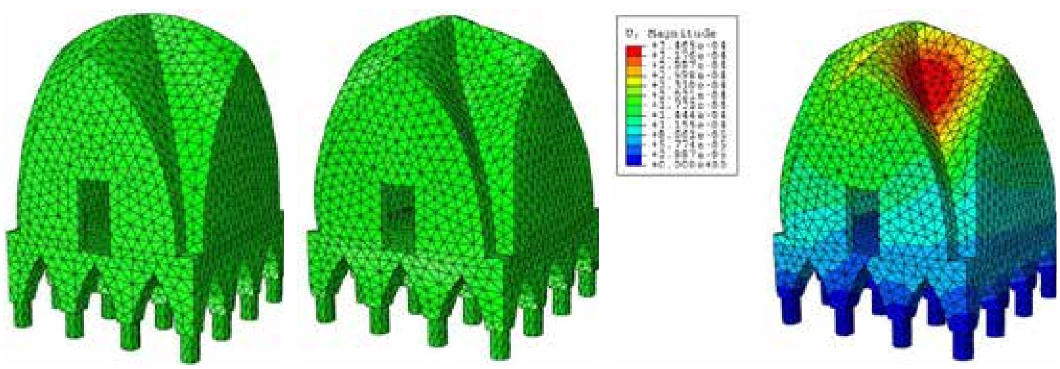


Figure 55. Wind load combination 3.

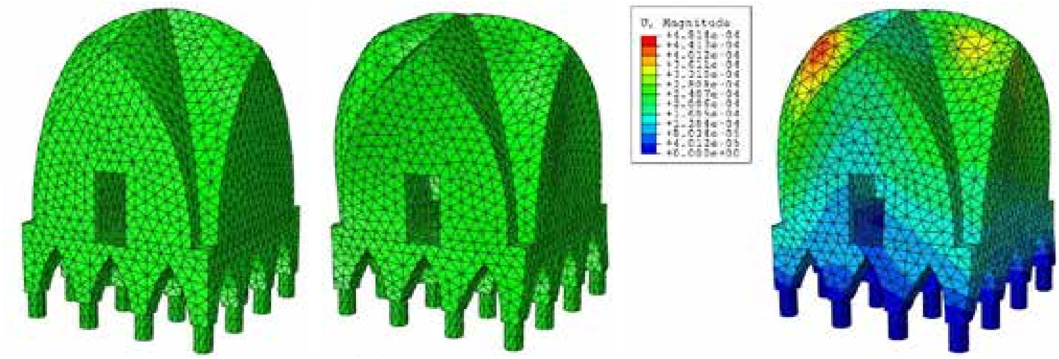


Figure 56. Wind load combination 4: Torsional effect included.

B. Forces And Moments for Load Wind Loads Combinations For Model D

Wind Load Combination: 1

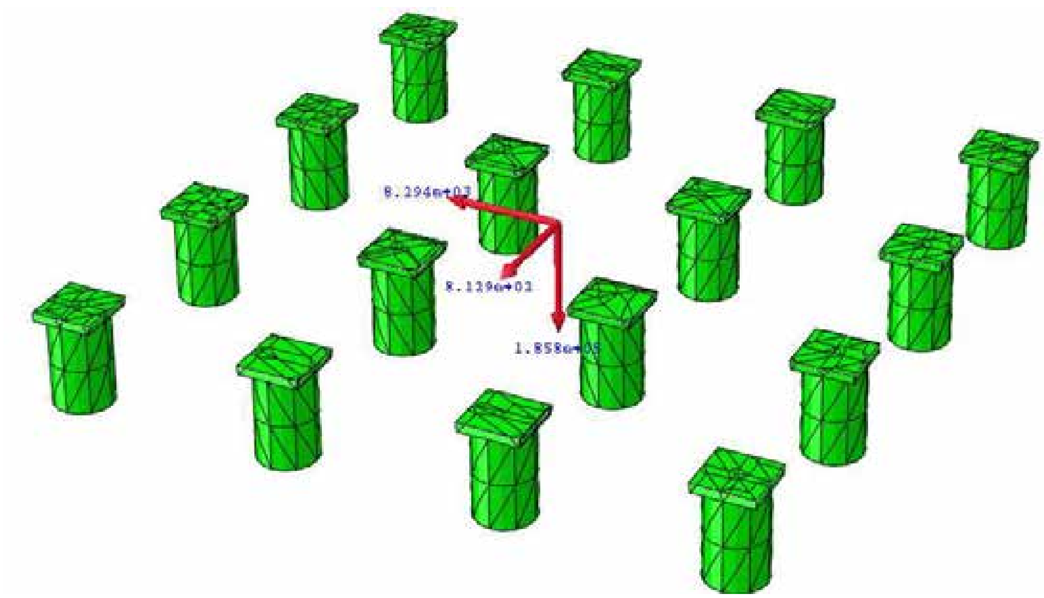


Figure 57. Force resultants at column base level for Wind Loading combination 1.

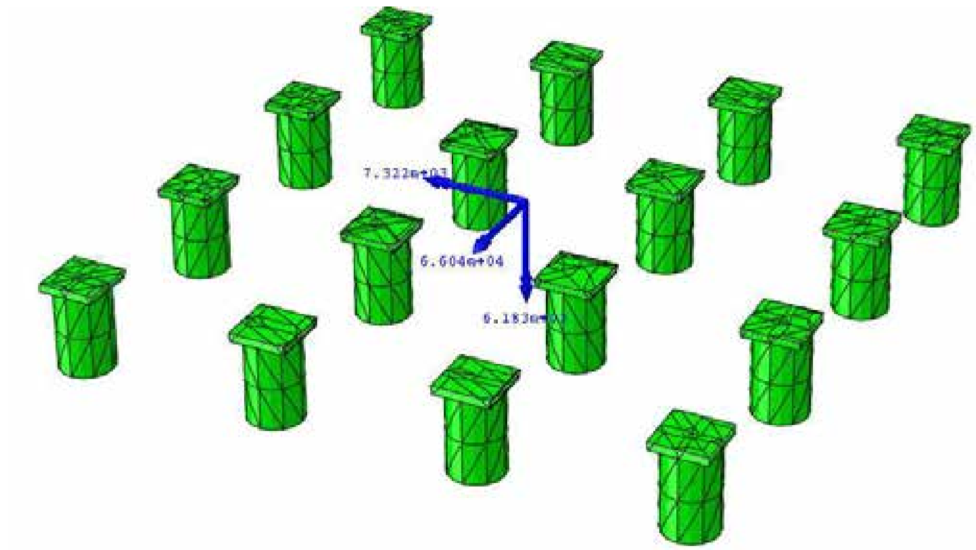


Figure 58. Moment resultants at column base level for Wind Loading combination 1.

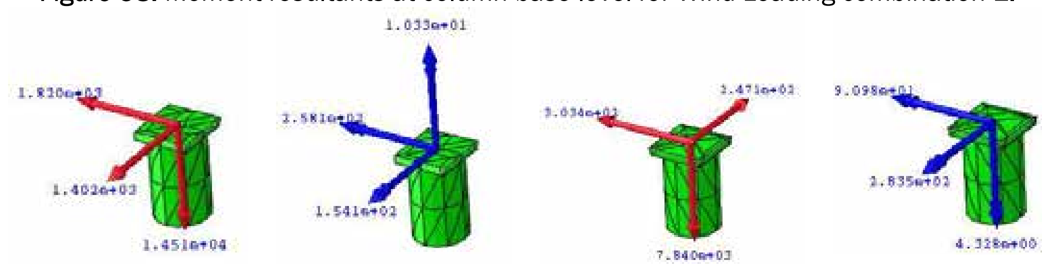


Figure 59. (a) Forces and (b) Moments for Column 1A; (c) Forces and (d) Moments for Column 2B.

Wind Load Combination 2: 0.75windward+0.75leeward+$M_{T,2}$

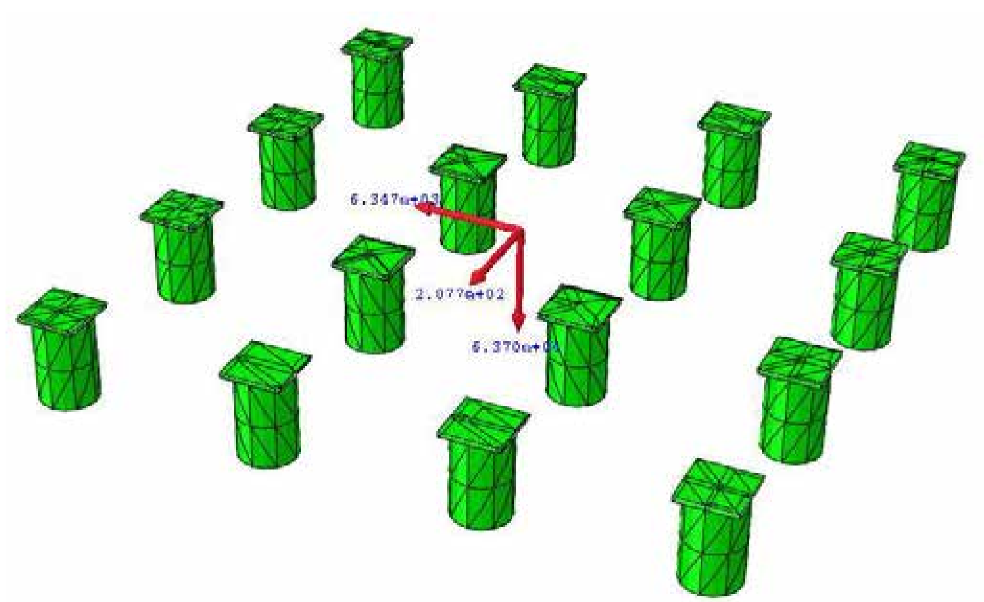


Figure 60. Force resultants at column base level for Wind Loading combination 2.

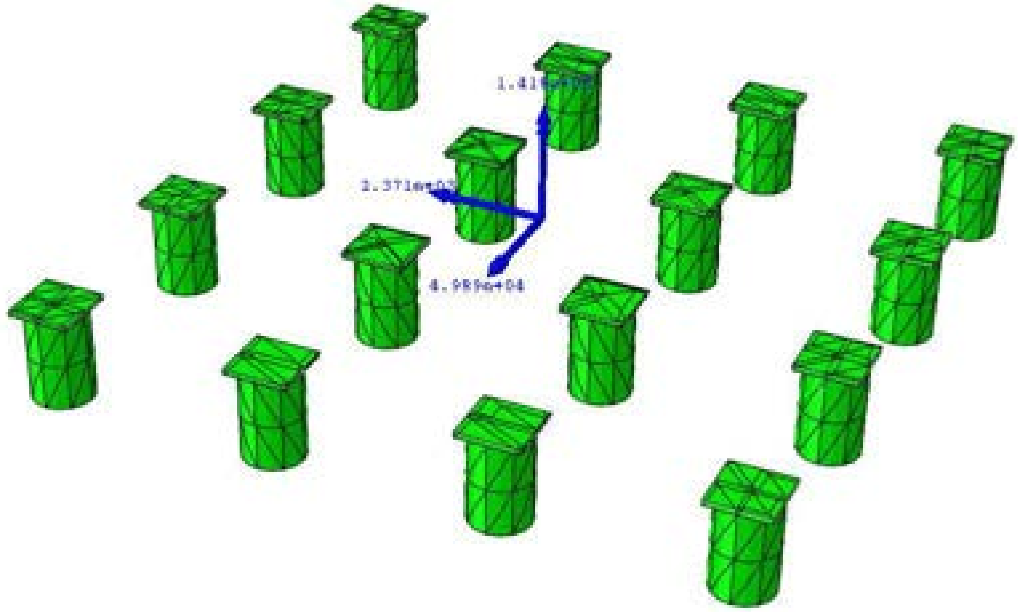


Figure 61. Moment resultants at column base level for Wind Loading combination 2.

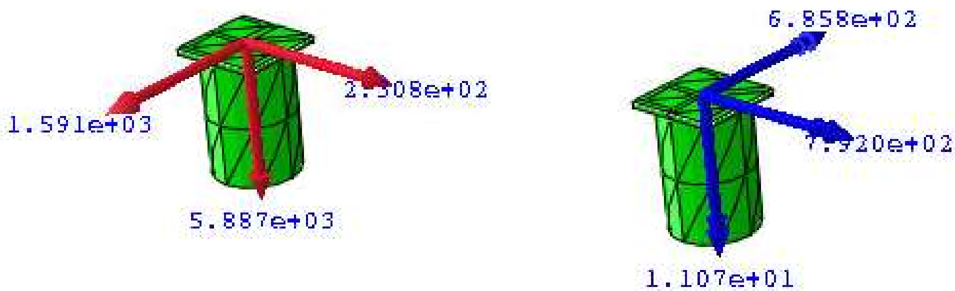


Figure 62. Forces and Moments in Column 1A for Wind Load case 2.

Wind Load Combination 3: (0.75windward+0.75leeward) X 2 Sides

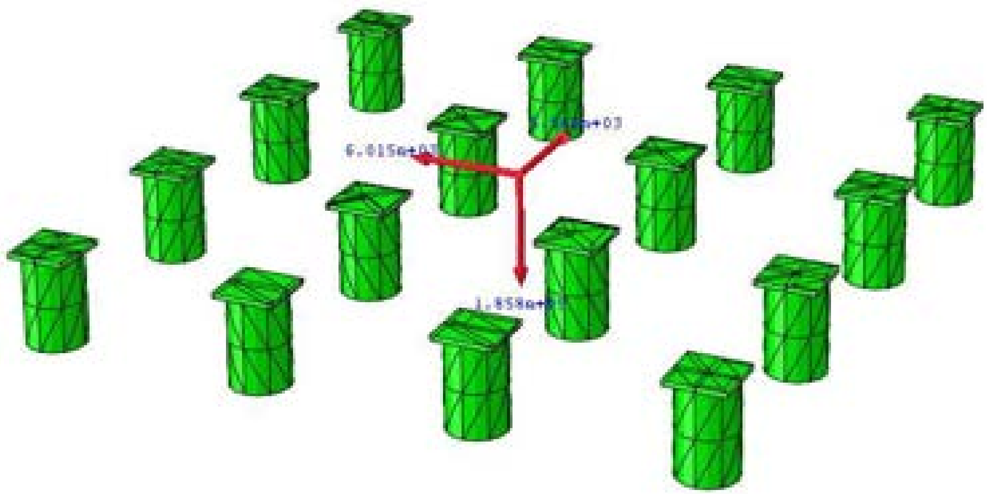


Figure 63. Force resultants at column base level for Wind Loading combination 3.

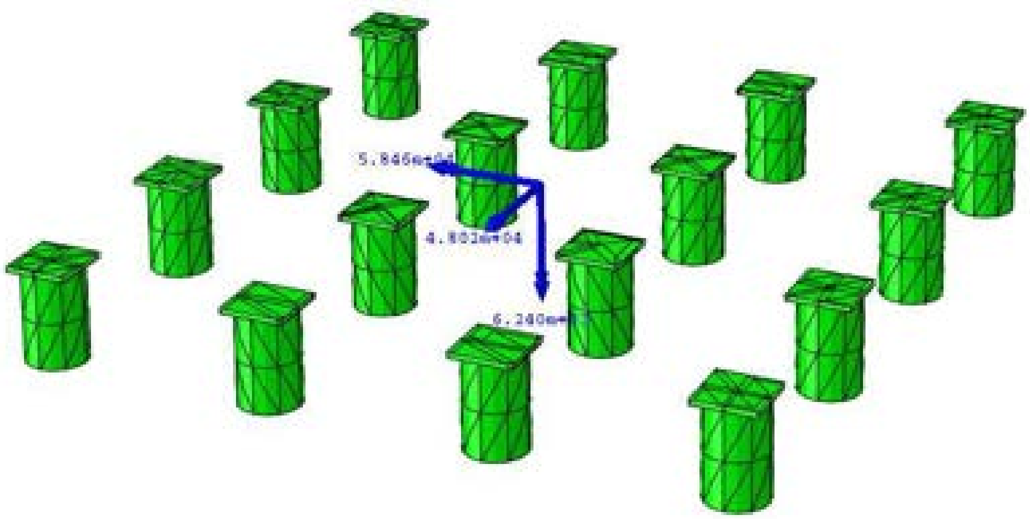


Figure 64. Moment resultants at column base level for Wind Loading combination 3.

Figure 65. Forces and Moments in Column 1A for Wind Load case 3.

Wind Load Combination 4: 0.50windward+0.50leeward+$M_{T,4}$

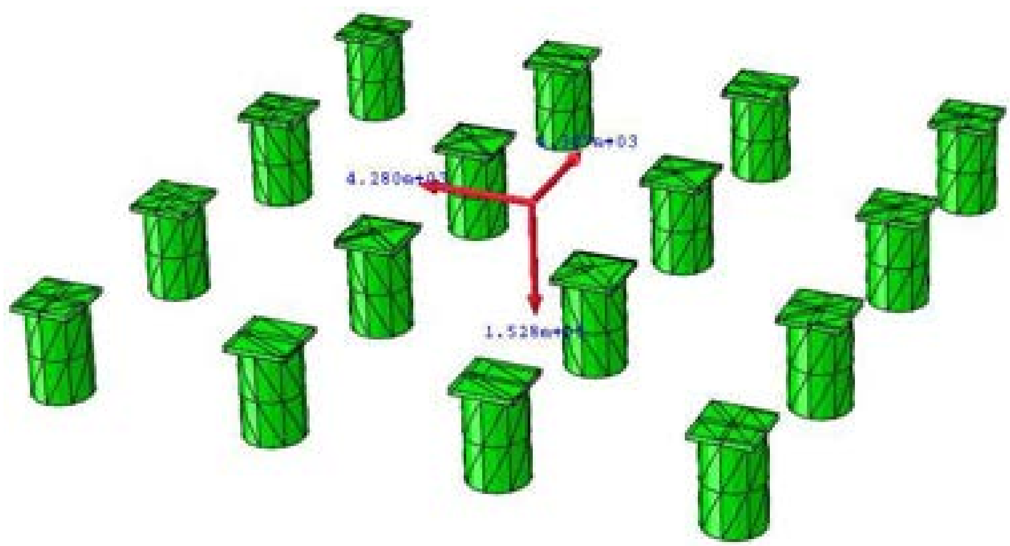


Figure 66. Force resultants at column base level for Wind Loading combination 4.

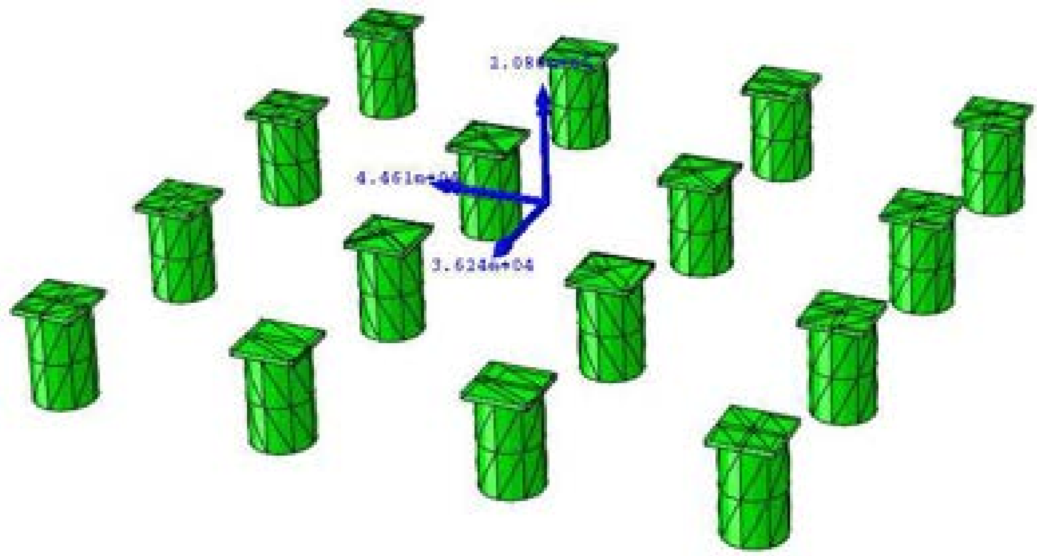


Figure 67. Moment resultants at column base level for Wind Loading combination 4.

C. Displacement Field For Load Snow Loads Combination In Model D

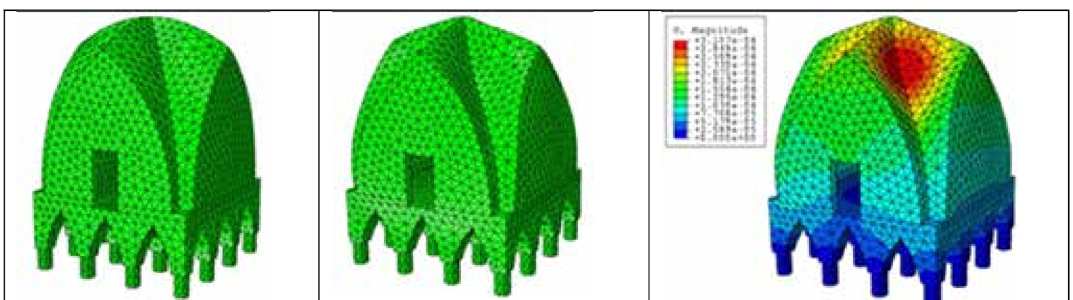


Figure 68. Snow load combination (Deformation scale factor: 6.468E+3).

D. Forces And Moments For Load Snow Load Combination For Model D

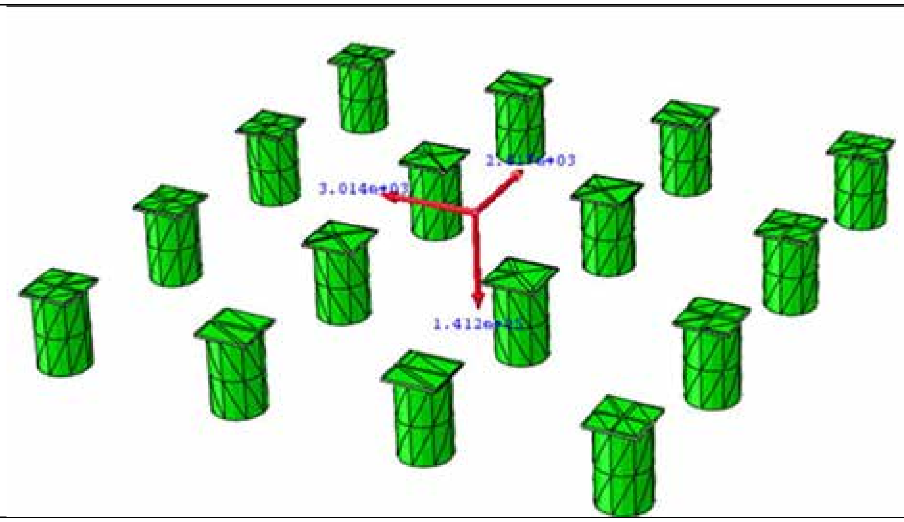


Figure 69. Force resultants at column base level for Snow Load combination.

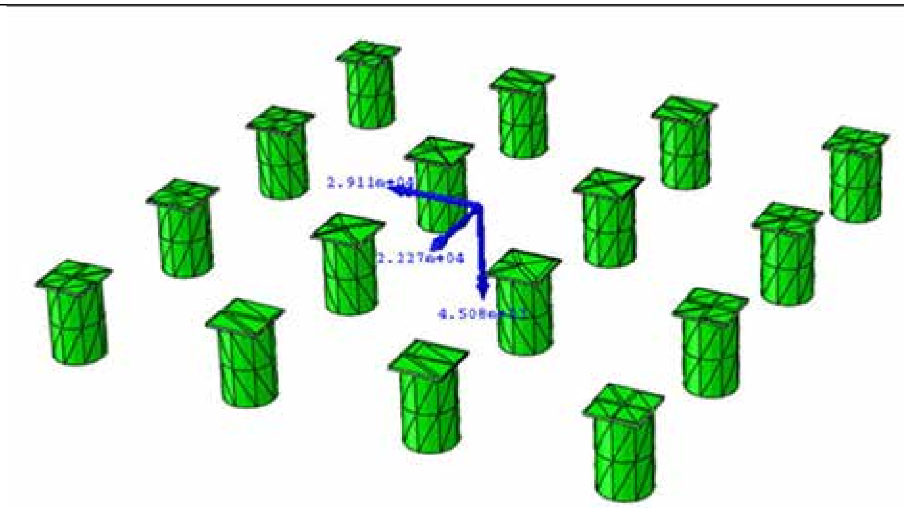


Figure 70. Moment resultants at column base level for Snow load combination.

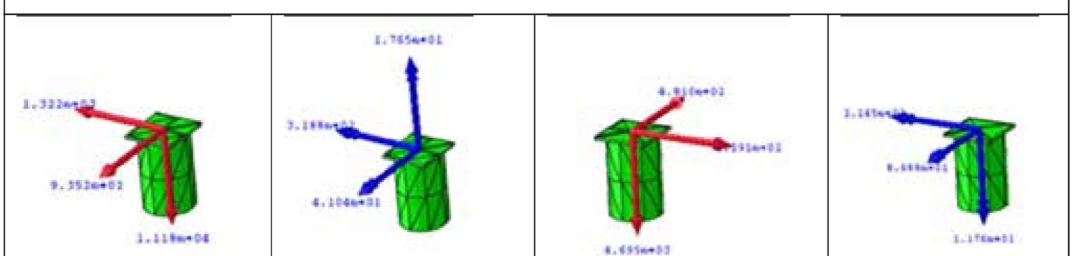


Figure 71. (a) Forces and (b) Moments for Column 1A; (c) Forces and (d) Moments for Column 2B.

Thermal Analysis to Evaluate Structure-Foundation-Soil Thermal Interaction

Permafrost Consideration

Figure 72 illustrates how a permafrost system can include complex components. The top seasonal freeze-thaw layer (i.e., active layer) has varying thickness (e.g., from approximately 0.4 to 1.0 m in North Slope Borough) and is underlain by a permafrost layer that can extend to a great depth. In a warming climate, the active layer thickness (ALT) increases. Some areas may have ice-rich permafrost with high volumetric ice content of 80%. Ice lenses and ice wedges may also exist. When permafrost thaws, groundwater drains and causes significant settlement (Wagner et al. 2018); the migrating groundwater freezes in the winter and causes unexpected and significant localized ground heave. These physical processes have resulted in wavy roads and tilting houses. The thermal, hydrological, physical and biological processes drive the variations in geophysical characteristics such as ground temperature, thermal conductivity, volumetric ice content, and geotechnical characteristics such as hydraulic conductivity, void ratio, elastic modulus, shear modulus, Poisson's ratio, and shear strength.

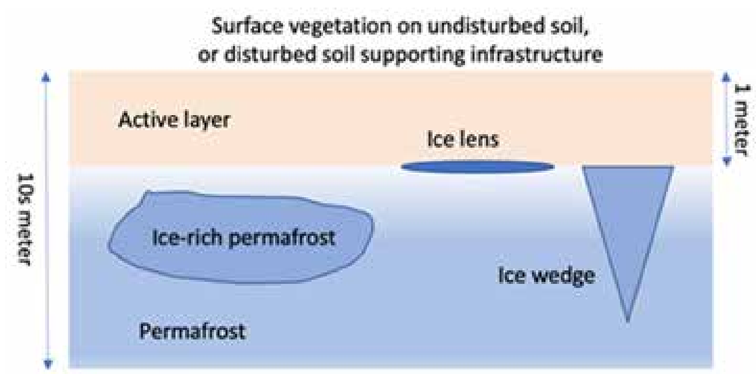


Figure 72. Illustration of permafrost system (not-to-scale).

Frost-stable coarse granular soils and rocks without ice inclusions are the best materials for foundations in cold regions. Frost heaving in uniform sands and gravels is generally negligible due to their high drainage capacity. At thawing, these materials are stable with good bearing capacity. The foundation design in such soils should follow the current practice of moderate temperature regions (Andersland and Ladanyi 1994). For fine-grained soils may contain significant amount of ice due to their poor drainage capacity; pore pressures generated during thawing may result in a significant loss of shear strength (Andersland and Ladanyi 1994).

Pile Foundation Design

Height Of Airspace: The airspace between the bottom of the house and the surface of the ground must be enough for unimpeded circulation of cold air. The height of the airspace depends on the size of the building and amount of wind. A small home of approximately 30-foot width should have 3 feet height of the airspace, and the minimum height is 2 feet. The aspect ratio of the minor dimension of the building to the airspace height should be less than 10 (McFadden 2001). For this habitat, the length of pile or post above ground should be at least 2 ft. The width of the habit is 12 ft, thus the aspect ratio is 6, which is less than 10 and good. Of course, the actual height above ground for Model D is larger than 2, which is more desirable.

Pile Type And Material: We recommend slurried pile as the pile foundation. Slurried pile has been the most commonly used foundation in Alaska (McFadden 2001). We suggest pressure-treated all-weather wood is used for the piles to limit heat transfer from the house to the permafrost foundation soil. The slurried pile is 6 inch in diameter. The hole of 12 inch in diameter is first drilled. The larger end of the wooden pile is at the bottom of the hole. The open space (annulus) between the pile and the drilled hole is filled with clean sand-water slurry and compacted using preferably vibratory compactor. If vibratory compactor is unavailable, careful tamping using long rods can be used. The clean sand-slurry should have 6-inch slump in order to achieve workable consistency and develop strong adfreeze bond. If clean sand is not available, the auger cuttings that are removed from the hold should be used for the slurry. In this case, wood, peat, or other organic materials should be removed from the cuttings that are used for the slurry. A concrete mixer can be used to prepare the slurry. Water should not be allowed to enter the hole. If groundwater is present, a casing should be used, at least in the active layer, to prevent water from flooding the hole.

We suggest pressure-treated all-weather wood is used for the piles to limit heat transfer from the house to the permafrost foundation soil. Local timber, generally spruce, Douglas fir, or pine, is most commonly used. They have length from 6 to 15 m (18 to 45 ft) and diameters from 150 to 250 mm (6 to 10 inch) at the top and 300 to 350 mm (12 to 14 inch) at the bottom. The timber piles usually remain well preserved in permafrost, but they must be protected in the active layer against deterioration and decay. Several wood preservatives may be used for that purpose, but some of them may reduce the adfreeze bond between pile surface and frozen soil (Ladanyi and Andersland 1994).

When soil freezes around the pile, a bonding force between the ice in the soil and the pile surface develops, known as adfreeze bond. Such bond is temperature-dependent, the colder the temperature, the higher the bond strength. Since the active layer becomes much colder than the permafrost in the winter, the adfreeze bond in the active layer is higher than that in the permafrost layer. Frost heave of the active layer can uplift the pile. The depth of the pile embedment in the permafrost layer must be greater than the active layer thickness. Most piling designs attempt to weaken or eliminate the adfreeze bond in the active layer by using sleeves or coating on the pile in the active layer. We recommend the pile in the active layer be wrapped with three layers of 6-mil thick black polyethylene film, which is commonly used in Alaska as an effective way to reduce the adfreeze grip (McFadden 2001). If black polyethylene film is not available, clear polyethylene film is acceptable.

If the wooden pile will float out of the hole when slurry is placed, the pile will be held in place while the bottom 3 to 5 feet of the annulus is filled until the slurry freezes to hold the pile in place. Then, the rest of the annulus will be filled with slurry.

Driven piles are not recommended for this project. In the North Slope Borough where the soil is colder and has high moisture content, difficulty of pile driving increases. It may also be difficult to access pile driving equipment. Driven piles are usually steel piles, which may be difficult or expensive to obtain in remote areas.

Pile's Bearing Capacity Evaluation: The cavity expansion theory, based on nonlinear isochronous stress-strain and strength curves of frozen soil (Ladanyi and Johnston 1974; Ladanyi 1975; Phukan and Andersland 1978) can be used to determine the ultimate point (end) bearing capacity of a pile foundation in permafrost (Ladanyi and Andersland 1994):

$$q_{ult} = p_0 N_q + c N_c \quad (15)$$

where p_0 = average initial total stress at the bottom of the foundation,

c = temperature-dependent cohesion,

N_q and N_c = bearing capacity factors.

For circular pile foundation:

$$N_c = 1 + \frac{4}{3}\left(n + ln\frac{2}{3\varepsilon_f}\right)$$

$$N_q = (1 + \sin\phi)\left(1 - \frac{n}{k}\right)^{\frac{n}{k}-1}\left(\frac{2}{3}\right)^{\frac{1}{k}}(kI_r\tan\phi)^{\frac{n}{k}} \quad (16),\quad (17)$$

where n = exponent of stress in power law equation, n >1 and n is determined experimentally,

e_f = failure strain, corresponding to the strain at the minimum creep rate or at the start of tertiary creep,

$$k = \frac{3}{4}(1 + \mathrm{cosec}\phi) \quad (18)$$

I_r = rigidity index,

$$I_r = \frac{4{N_\phi}^{0.5}}{3\epsilon_f^{1/n}[1 + (p_0/c)\tan\phi]} \quad (19)$$

f = internal friction angle of the permafrost,

$$N_\phi = \tan^2\left(45^o + \frac{\phi}{2}\right) \quad (20)$$

In the bearing capacity calculation, the following parameters are used:

- f = 20º for sandy permafrost
- c = 200 kPa (or 4178 psf), a conservative value for sandy permafrost
- Unit weight of soil: g = 95 pcf
- e_f = 0.1 (Ladanyi and Andersland 1994)
- n = 2
- pile diameter = 6 inch
- Total weight of habitat: W = 82870 lb (Model D), 69,300 lb (Model B)
- Number of piles, N = 16
- Stress on each pile, q =6600 psf for Model D and 5517 psf for Model B (see note below)

The weight of the habitat Model D (Model B results in parenthesis) is 82,870 (69,300) lb. The habitat has 16 piles; each pile carries 5179 (4331) lb. Considering seismic-induced loading, the finite element analysis shows the worst axial load on a perimeter pile is 20,960 lb (13460 lb) compression and 13,960 lb (6610 lb) tension. Taking the worst case, for Model D (20,960 lb), the stress on the pile supporting this column for a pile of 6 inch in diameter is 26,700 psf (17,146 psf). However, under gravity alone, the stress is 6600 psf for Model D and 5517 psf for Model B.

The habitat may be built in three locations in Alaska (North Slope Borough, Fairbanks, Anchorage). The following Table 11 is prepared for the pile foundation's bearing capacity evaluation, and it shows the factor of safety by dividing ultimate bearing capacity for each region by the pile stress 6600 psf. For gravity load only, the factors of safety are all larger than 4, which is conservative. For seismic load, however, the least factor of safety would be 1.15 under compression. To consider potential tension in pile, we can simply determine the friction in the permafrost region by multiplying the cohesion coefficient of 4178 psf by the surface area of the pile in permafrost region, say 6 ft embedment, which results in approximately 39,000 lb, significantly larger than the potential tension due to the seismic effect.

Table 11. Soil Bearing Capacity in Different Regions

Locations	Active layer thickness, L_a (ft)	Embedment of pile in permafrost, L_p (at least 2 times of L_a to resist heaving, per Figure 14) (ft)	Total pile embed-ment (ft)	q_{ult} (psf)	Factor of safety: FS $=q_{ult} / q$
North Slope Borough	3	6	9	30,700	4,65
Fairbanks	4	8	12	32,222	4.88
Anchorage	5	10	15	33,699	5.11

Conclusion: the pile foundation is sufficient to support the superstructure load.

Material Testing and Analysis to Evaluate Selection and Use of Local Geologic Materials in Different Alaskan Regions for 3D Printing of Concrete Construction

The first batch of cylinders was cast on March 21st, 2021 and have been received in lab a week later (Figure 73). Since the samples were shipped in molds, they were demolded and then cut to ensure flat surface for testing. The information provided for the samples (coded) is as follows:

F=Fairbanks
A=Anchorage
J=Juneau
X=XHI binder mix
C=Control of 1 part Portland Cement, 5 parts contractor sand <=3.2mm and 1 part water.

The Alaska aggregate in samples has <=3.2mm diameter. The aggregates have been obtained based on crushing rocks. For practical printing, it is possible to use aggregates available at the site with dia. less than equal to 3.2 mm. On the other hand, if the rocks are to be used for crushing to get the needed size (<=3.2 mm), much more effort will be involved.

For each mixture design, compressive strength was evaluated, following ASTM C39-21. It is envisioned that for future testing of each mixture design, compressive and splitting tensile strength will be evaluated, following ASTM C39-21 and ASTM C496-17, respectively. It is envisioned that at least two cylindrical samples with length to diameter ratio of 2:1 will be tested at 7 and 28 days.

Figure 73. First batch of 6 by 12 in. Cylinders, as received.

Mechanical Strength of the First Series of Cylinders

All cylinders, after sample prep and trimming were tested to failure on April 19th, at approximately 28-days. Table 12 summarizes the results:

Table 12. Results of Cylinder Testing

Sample	*Height [in]*	*Length/ Diameter*	*Correction Factor*	*Strength [psi]*	*Corrected Strength [psi]*
C	10.664	1.777		520	
A-1	9.577	1.596*	0.9715	700	680
A-2	8.900	1.483*	0.9579	1060	1015
J	11.220	1.871		540	
F-1	9.300	1.551*	0.9661	570	550
F-2	10.348	1.725*	0.9870	250	247
X	10.643	1.774		640	

*if length to diameter ratio is less than 1.75, multiply strength by the correction factor

Based on the results of compression tests, the mixtures provided have resulted in significantly lower than needed compressive capacity. Our assumption for compressive capacity for structural modeling and calculation has been based on 2500 psi concrete, which is a conservative assumption. Our own mixture provides capacities higher than this value, but for structural calculations, it is preferred to be on the conservative side. It is recommended that for follow-up concrete mixture design, significant additional testing be carried out to ensure the locally available aggregate and the rest of mixture ingredients provide capacities higher than the minimum of 2500 psi. This may require extensive variation of ingredients percentages following a trial-and-error approach, meaning that we need to vary percentages of various ingredients gradually and testing properly cast cylinders until we reach and exceed the target capacity. Furthermore, for the mixture designs that do exceed the target compressive capacity, we need to test for modulus of rupture, printability, buildability, extrudability for the printing process, and then additional tests for serviceability performance once the structure is built and is assumed to be in use. Such tests could include thermal resistance, moisture permeability, durability, acoustic, etc.

3D Printing Related Issues

Scale Model Printing In Lab

Printing system in the Lab The printing system to be used in the printing operations will be a modified version of the system currently being used in the Penn State AddConLab, diagrammed in Figure 74. In its basic configuration, the 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 6-axis robot arm. The dimensions of the printing area can vary depending on the length of extensions added to the robot arm, which can be adjusted to fit the size of the structural unit. In another more elaborate configuration (Figure 75), 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 place opening frames and installations. In yet another configuration (Figure 76) the system may include a second mixer–pump and a second silo, to enable the printing of mixtures with a functional gradient. 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, and by varying the relative speed of each pump, it is possible to change the gradient of the printing mixture. To increase the mobility of the printing system, these configurations will be redesigned into a “printer-in-a-box” system (Figure 77). In such a configuration, the printer system can be moved using standard shipping methods.

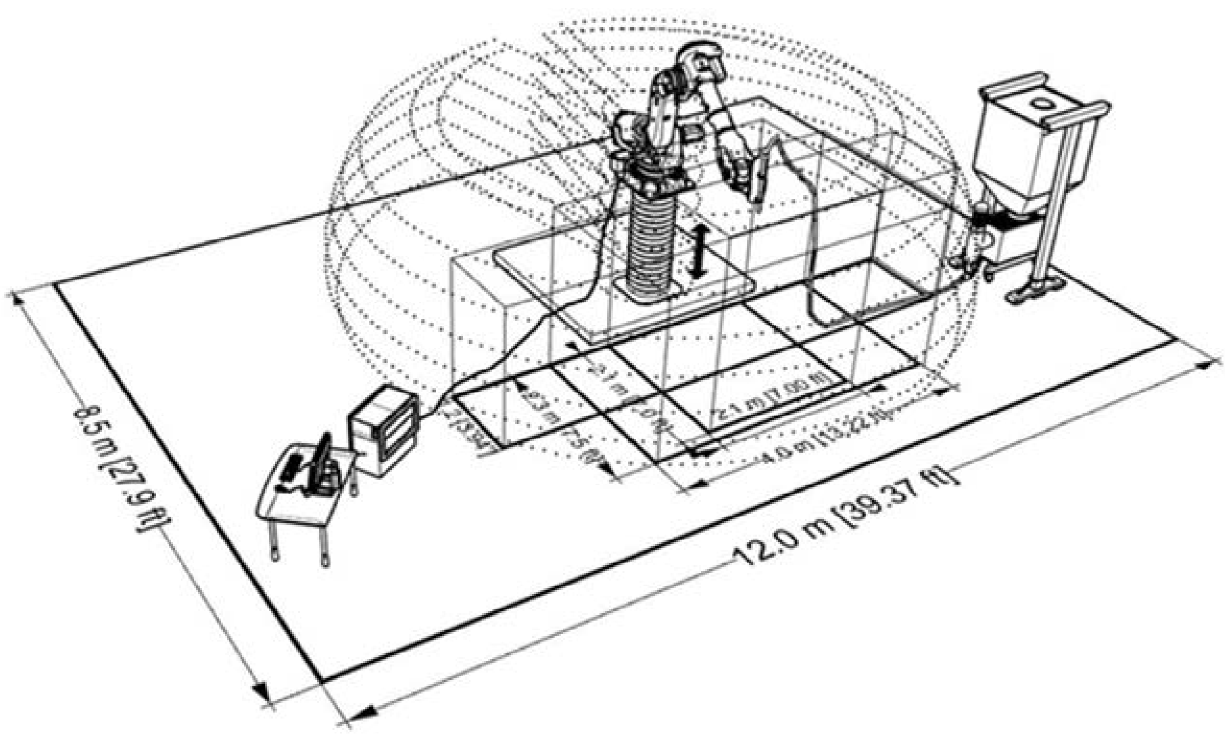


Figure 74. Diagram of the basic configuration of the printing system currently installed at the Penn State AddConLab, which includes a mixer-pump, a small silo, and a robotic arm. The printing area will be increased to meet the size of the proposed structural unit by increasing the extension of the robotic arm.

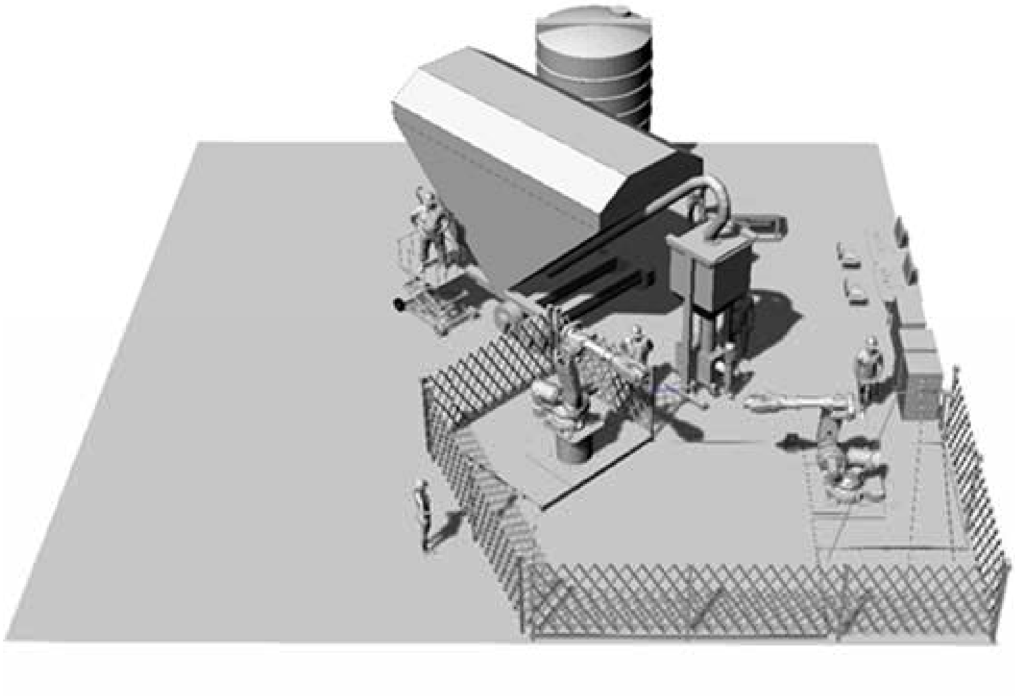


Figure 75. Diagram of the configuration of the printing system used by the Penn State AddConLab to print a structural unit 26′ × 13′ × 13′ in size. In this configuration, the system also includes a second robotic arm, a large silo, and a water tank.

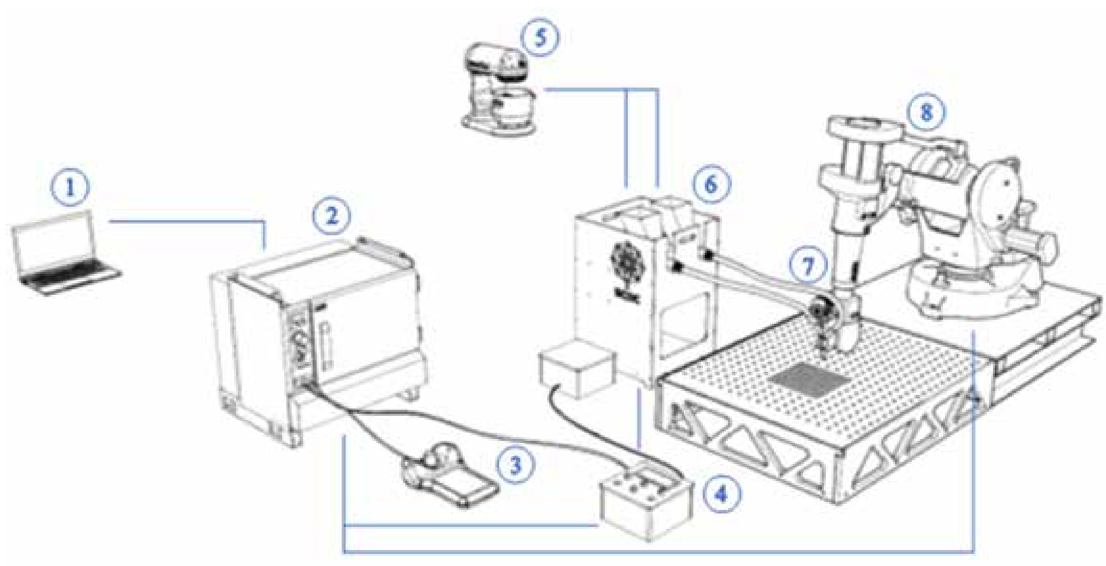


Figure 76. Diagram of the printing system for functionally graded materials used at AddConLab: 1. Computer for designing the graded material and the toolpath, 2. Robot controller, 3. Robot tech pendant for hand control, 4. Pumps' tech pendant for hand control, 5. Mixer for materials preparation, 6. Concrete pumps, 7. Dynamic mixer/extruder nozzle, 8. Robotic arm. This system will be scaled up to meet the size of the proposed structural unit.

Printing system in Alaska

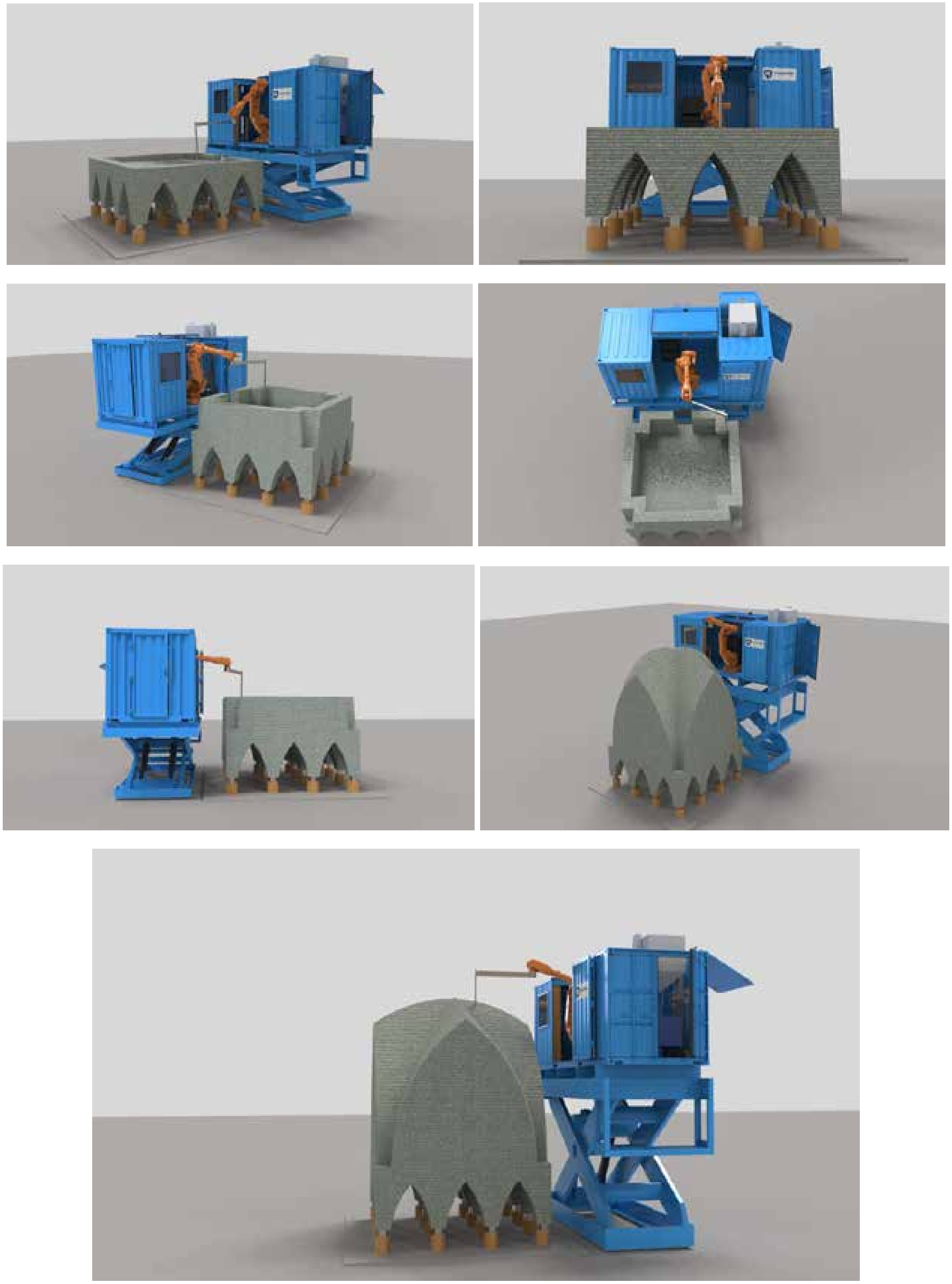


Figure 77. Printing process of the proposed shelter at different stages of completion. The depicted "printer-in-a-box" system is currently being developed to facilitate deployment and mobility.

Materials

Penn State AddConLab has developed and worked with different kinds of mixtures for 3D printing, including cementitious, non-cementitious (i.e., geopolymer), and clay-based mixtures. 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 Portland cement, lime, pulverized limestone, especially graded masonry sand, fibers, and admixtures (Table 13) with a maximum particle size of 1 mm.

Table 13 - GCT material composition

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%

Material properties of the concrete with this mixture, including compressive strength, the setting time, and the material flowability, are presented in Table 14. 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. ASTM C39 test obtained within 48 hours of printing the concrete structural elements performed on a printed cylindrical specimen showed 749 psi compressive strength, and ASTM C78 performed on a printed rectangular beam showed 485 psi (Modulus of Rupture).

Table 14 - GCT material properties

Compressive Strength	Test Age (d)	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	

In addition, Penn State can work together with Xtreme in Phase 2 of this project to develop and test their own printable mixture with appropriate, rheological and strength properties.

Toolpath design

Concrete printing involves a complex system of interdependent variables concerning the printing system, materials, and design. Successful printing of stable and accurate forms depends on tuning the system to the right combination of values for such variables (Figure 78). 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 included the dry mix feed and water flow rates, which determine the proportion of water to dry mix and, together with the pump rotation speed and the nozzle section, condition the robotic arm speed. Basic information regarding the relationships between these variables, help to determine adequate printing settings, including pump flow rate and robot speed, for a given nozzle size.

Penn State AddConLab has developed research to obtain this information and model the relationships among the different system variables. This research led to software to automatically generate toolpaths that guarantee high printing quality by accounting for material deformation (Figure 79), 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 layers and filaments.

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 industrial robots. Robots have two operating modes: manual mode, in which the manipulator movement is under manual control and the speed is reduced to a maximum 250 mm/s; and automatic mode, in which the safety function of the three-position enabling 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 completely “autonomous”.

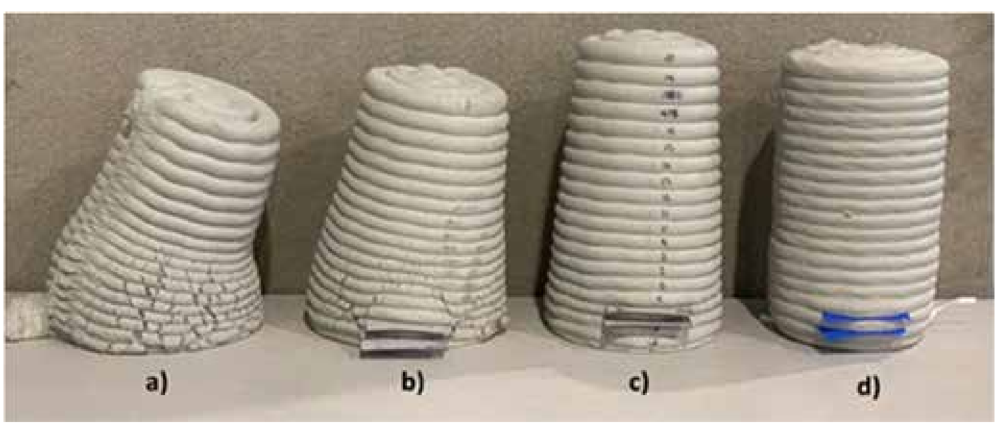


Figure 78. Cylinders printed with toolpaths with no compensation (a), compensation for layer height deformation only (b), compensation for both layer height and width deformation (c), and compensation for time dependent deformation (d).

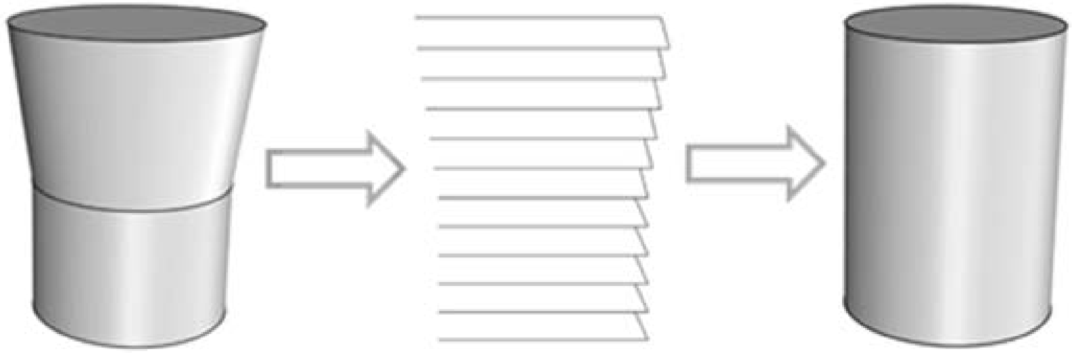
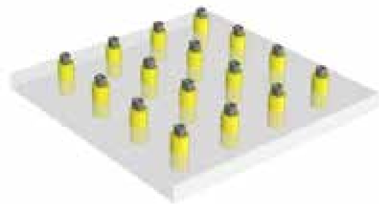


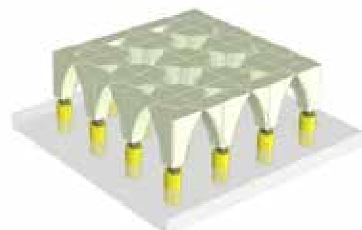
Figure 79. Diagram representing the strategy for designing a cylinder with compensation for layer width deformation: compensated designed cylinder (a), compensated toolpath (b), resulting printed cylinder (c).

Construction sequence

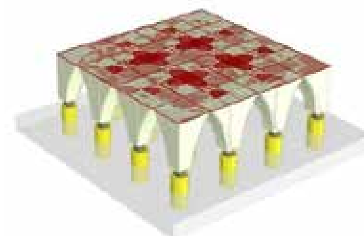
The construction of one unit with a double shell is depicted in Figures 80 and 81 The process starts with the placement of piles into the permafrost soil followed by the jack connectors (1), then proceeds with the printing of the grounding shell (2), which is then filled with lightweight concrete (3). This makes the structure lighter and if the lightweight concrete has insulating beads, it can provide some thermal insulation properties. Of course, thermal insulation of the structure is provided in the interior. Next, the floor slab is printed on top (4), then the base wall (5), followed by the placement of the opening frame (6). Then the printing of the roof structure is initiated (7). In the solution 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, 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.



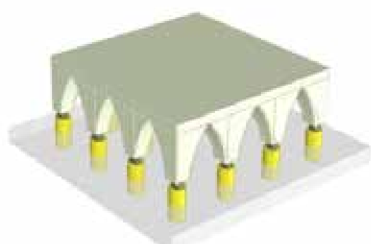
1. Placement of piles and connectors



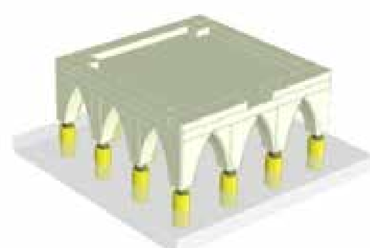
2. Printing of concrete grounding



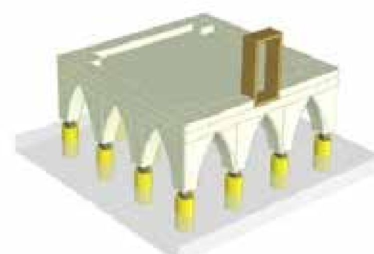
3. Pouring or printing of light-weight concrete infill



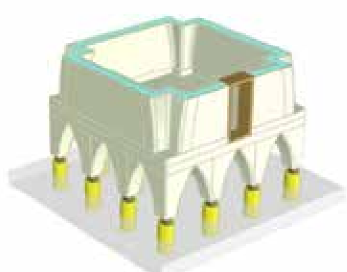
4. Printing of floor slab



5. Printing of wall base

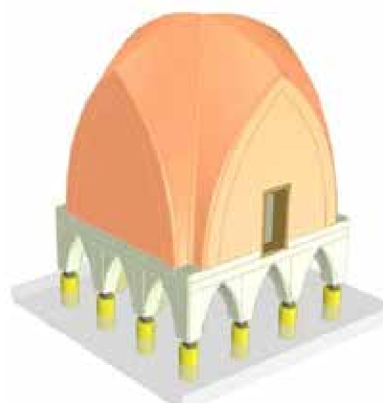


6. Placement of door frame



7. Printing of double shell and pouring of insulation

8. Complete printing of cross-vault



9. Spraying of external wall coating (polyurea)

Figure 80 – 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.

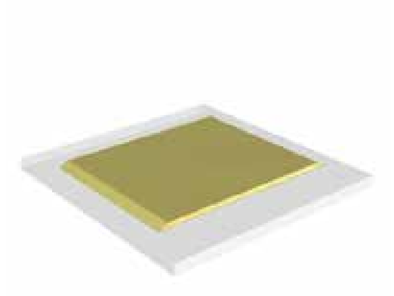
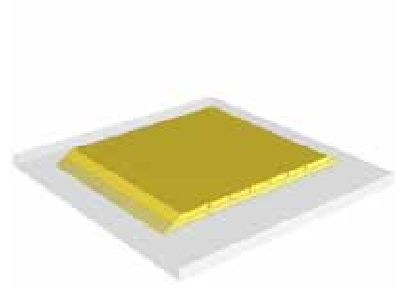
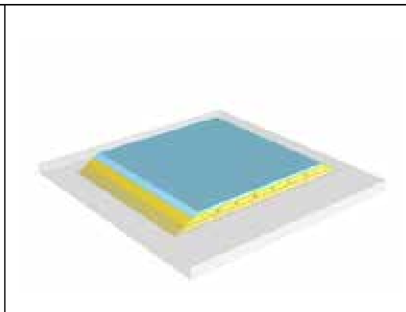
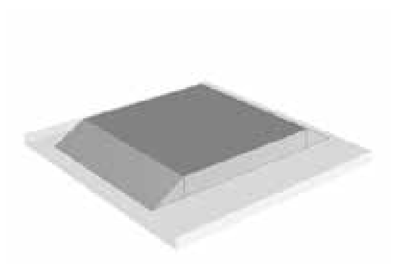
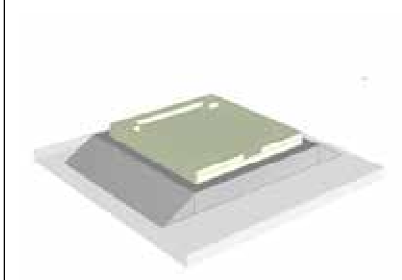
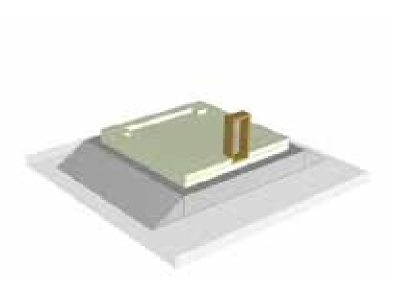
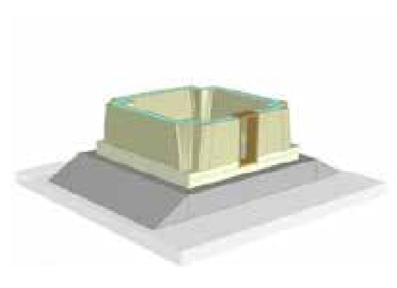
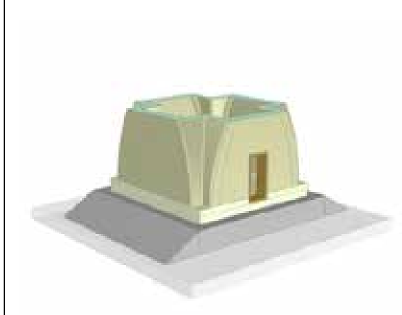
		
1. Layering of compact sand	2. Placement of cooling tubes	3. Placement of XPS
		
4. Layering of clean grave	5. Printing of concrete floor slab	6. Printing of wall base
		
7. Placement of door frame	8. Printing of double shell and pouring of insulation	9. Continued printing of double shell and pouring of insulation
		
10. Complete printing of cross-vault	11. Spraying of external wall coating (polyurea)	

Figure 81 – Construction sequence of a slab on grade, 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.

Larger houses can be obtained by incrementally adding new units (Figure 82). 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 household increase. Houses may acquire different configurations as different number of units may be added on different sides. It is also noteworthy to mention the possibility of combining units with different roof shapes.

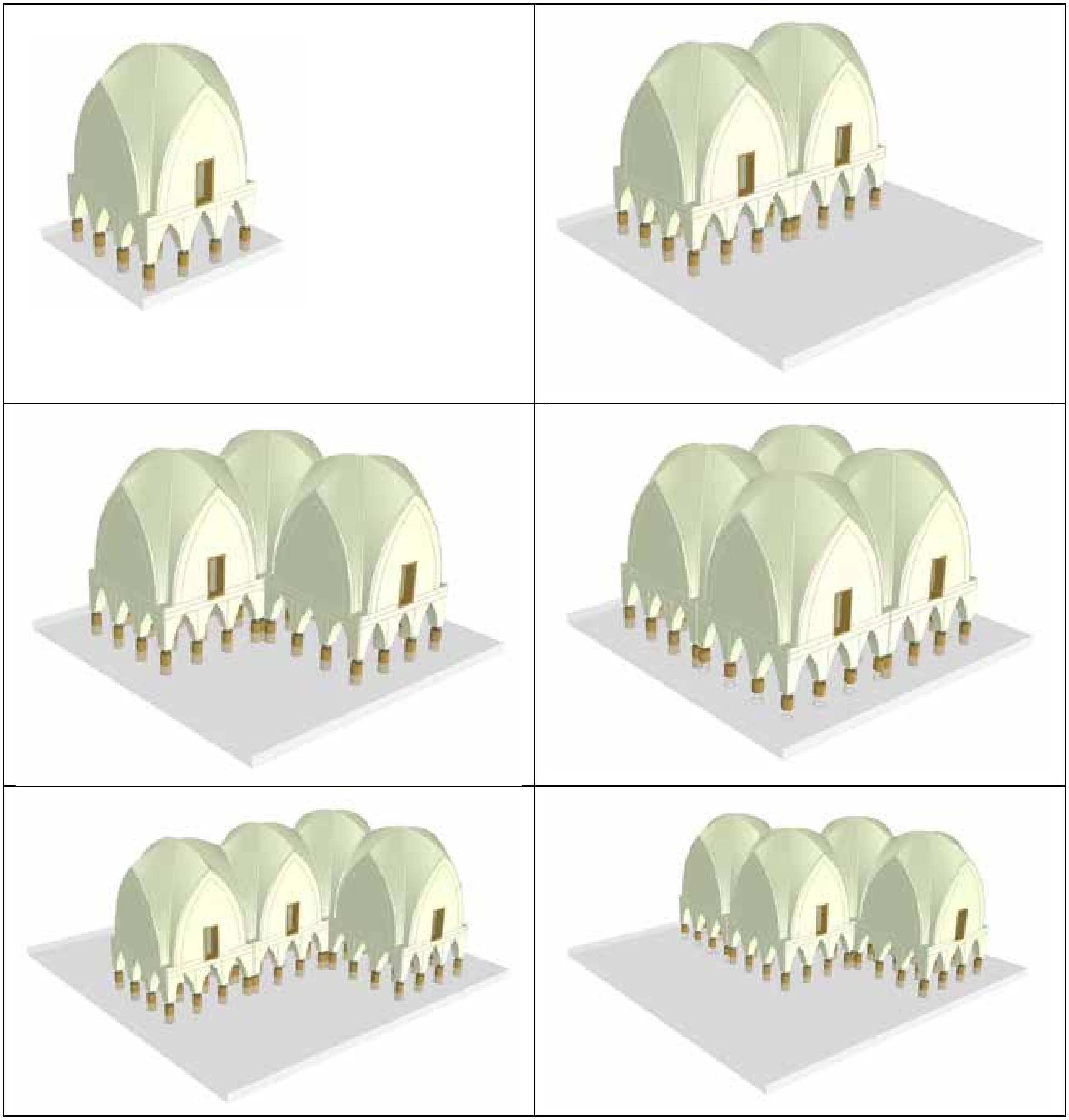


Figure 82 – Incremental addition of units to form larger houses, which may occur over time and take different configurations. Each unit may have different and one or more uses: kitchen, living-room, dining-room, bedroom, bathroom, and so on. The exact configuration and uses will depend on the household profile, including the number of members and social-economic level.

Recommendations

Choice of Sealant to Protect the Structure Against the Harsh Weather Conditions

We propose the application of Polyurea which is a product with several desirable attributes to protect the entire structure as it provides protective lining, a barrier coating, water proofing, and enhances the surface performance and function with respect to abrasion, load, and impact. Polyurea's coating thickness can be finely controlled [Prabhu 2020], it has suitable adhesion properties with concrete, and makes a desirable sealant, joint-filler, and calk for any surface. It is corrosion-resistant, abrasion-resistant, and is crack-resistant. Polyurea can be applied to a variety of materials such as wood, steel, and concrete. Its feasibility of low viscosity enables mixing and spraying at desired temperatures. In addition, transparency of Polyurea enables us to maintain the aesthetics of the exposed 3D printed concrete structure where desired, while sealing, protecting, and enabling easy maintenance and upkeep of the interior and exterior.

Concrete is a composite material with complex chemical structure. The composition that is needed for 3D printing is even more complex because it has to be specifically designed for 3Dprinting to accommodate flowability, printability and shape accuracy after deposition. This means that different admixtures are used to achieve just the right balance of properties needed in the mix.

As mentioned in the previous sections of the report, we are exploring various schemes in which we may have parts that are printed and other parts that may be poured in place inside a printed shell to achieve the needed structural and thermal performance. To achieve the desired properties, there will be several mixtures of concrete (functionally graded or layered with different properties). As such, the Polyurea used to seal these various compositions of concrete may need to be adjusted to accommodate for such differences in various types of concrete and other materials used in the foundation such as wood and steel joints.

If we chose to construct raised habitats in permafrost regions, the foundation would preferably consist of wooden piles that penetrate the permafrost, above which there would be a mediating adjustable steel joint before the 3Dprinted structure begins. The adjustable joint comprises of a steel cap on top of the wooden pile, an adjustable jack, and a steel plate. The 3D printed vaults above this joint continue to raise the structure approximately another 3' before the floor slab appears. In this scenario, we would seal the foundation, the underside of the raised slab, and the shelter's exterior surfaces with Polyurea. The use of Aqua Seal Polyurea lining would provide a seamless monolithic membrane to protect the shelter and any other structures we would print against harsh weather, snow, and ice. This seamless monolithic membrane could continue to unite the exterior and interior to protect the floor(s) and the interior concrete walls. It is possible to use a non-stick coating of Polyurea (Polyshield HT™ Traffic Coat with small aggregates) on the floors in areas which might get slippery when wet, for example in the bathroom and kitchen to protect people from slipping and falling. Interior surfaces of Cisterns and/or sceptic tanks can also be protected with special variations of Polyurea that are chemical or fuel resistant.

Polyurea can be formulated to provide special characteristics to solve many coating challenges. It has beneficial tensile elongation characteristics (measures of both elastic deformation and plastic deformation), which is commonly expressed as a percentage. It is used in conjunction with stress and strain values to help determine the mechanical properties of a material when performing a tensile test.

It is important to note that Hybrid Polyurea products that may be less costly, may lack sufficient moisture resistance, high temperature resistance, or other desired characteristics when compared with pure and other utility infrastructures.

In addition, Polyurea can also be formulated to have a very high tensile strength, resists bacteria and viruses, and also absorb impact energy, "Some polyurea products provide a tough coating and are capable of strengths of 6000 psi (40MPa) tensile and more than 500% elongation. Several coats can be applied to a surface quickly due to polyurea's fast drying or cure time. A property of one polyurea elastomer-based material is its melding together or "self-healing" ability. Even when the material is cut, it can fuse or back together again, and this re-bonding process can be repeated. Polyurea is more than a product. It is a technology." [see: https://sprayfoaminsider.com/Polyurea.php]

Timing and Staging of Application of the Primer Coats and the Final Polyurea Coat

Primers are applied several times onto porous substrates such as concrete to minimize outgassing, to seal the surface, to eliminate or reduce pinholes in the polyurea. Although most of the formulated polyurea spray coatings provide very fast cure even at temperature extremes of about 0°F and up to +250°-300°F, experience has shown that the timing of the application of the primer, the subsequent primer recoats, and the actual final polyurea coating is sensitive and dependent on the surface and ambient temperatures. As such, there is a window of time during the day when the application needs to start. This is because when polyurea is being applied with the high-pressure spray system, it has a temperature of well above 200 degrees Fahrenheit. The chemical reaction between the concrete surface and the chemical that is being sprayed causes the concrete to heat up to about a 160-170 degrees Fahrenheit, which in turn raises the temperature of the air inside its porous mass, causing it to expand and escape, which can result in air bubbles that burst causing a pin-hole effect on the polyurea if it is applied to the surface undermining the needed sealed condition. Timing between the primer recoat and final coat is also critical to get a good bond between the primer and final polyurea coat. When the sun is rising, the concrete surface begins to heat up, resulting in the air inside to expand and get out of the pours (exhales). Primer should not be applied during this time. Instead, the primer must be applied as soon as the ambient temperature begins to fall causing concrete to cool down to take the primer deeper inside its porosity (while it is inhaling). [see https://vimeopro.com/polyurea/polyurea-training-videos/video/417354482]

Choice of Materials for Insulation

We are considering spray-foam insulation with very high R-Values. "Open-cell spray foam insulation contains fewer chemicals and is often less expensive. While it is a good air barrier, it is not a good solution for a water vapor barrier. Open cell spray foam is most often used for interior walls since it provides noise reduction. Closed-cell spray foam insulation is an excellent barrier for air and water vapor. It is excellent for outdoor use, but it can also be used anywhere throughout a home or building where insulation is needed."

"Spray foam insulation is a two-component mixture that creates an expanding foam when it is combined through a spray gun. Because of the material's expanding qualities, it is typically used as an insulator for walls, floors, ceilings, roofs, crawl spaces, cracks, crevices, cavities, confined spaces, and concrete slabs. Spray foam insulation is highly energy efficient and lowers utility costs. It can provide as much as 50% more efficiency as compared to traditional insulation products. Moreover, it is used to control moisture and noise reduction."

It is necessary to comply with and exceed the minimum insulation requirements in Alaska. Use of the Prescriptive Method that does not dictate specific building methods or materials. Any method of constructing a building may be used provided clear compliance with the minimum insulation requirements is shown. As the means of compliance for the Alaska State Thermal Efficiency Standards, all mandatory measures given in Chapter 2 of the Building Energy Efficiency Standard should also be accomplished. [Building Energy Efficiency Standard. State of Alaska Department of Community and Regional Affairs, September 1, 1991.]

"R-value minimums refer to the installed R-value. Compression of some insulating products results in a lower R-value. For example, placing a standard R-30 batt into a 2x8 wall compresses the batt from 9 inches down to 7-1⁄4 inches. This results in a decreased R-value from the listed R-30 down to approximately R-26."

In table below (Table 15), R-value minimums refer to the installed R-value which may be different from the listed product R-value. Higher R-values may be used if desired.

Table 15. REF_A_Building Challenges in Alaska_HCM-00952

Region Number	Region Name	Heating Fuel	Thermal Envelope R-Value Requirements							
			Ceiling	Above grade Wall	Floor	Below grade Wall	Slab Floor		Window	Door[1]
							Base-ment	On-Grade		
1	Southeast	All Fuels	38	21	30	15	10	15	3.0	2.5,7
2	Southcentral	Natural Gas	38	18	19	10	10	10	3.0	2.5,7
2	Southcentral, Aleutian, Kodiak	All Fuels other than natural gas	38	25	30	15	10	15	3.0	2.5,7
3	Interior, Southwest	All Fuels	38	25	38	19	10	15	3.0	7
4	Northwest	All Fuels	38	30	38	19	10	15	3.0	7
5	Arctic Slope	All Fuels	52	35	43	—	—	—	3.0	7

Note:

1. Not more than one exterior door in a residential building in regions 1 or 2 may have an R-value less than 7, but not less than 2.5.

Choice of Vapor and Moisture Barrier:

The application of polyurea as a finish provides a strong moisture and vapor barrier and can substitute the recommended 6-mil polyethylene vapor barrier that Seifert (2000) recommends to be installed over all interior surfaces directly over the insulation prior to installation of partitions and interior finishes book *Special Considerations for Building in Alaska*. It is important to note that this is a long-term solution as polyurea has shown to have a 75-to-100-year life cycle (Primeaux and Assoc).

Choice of Ventilation: [see https://tinylifeconsulting.com/properly-venting-a-tiny-house/]

"1. Ventilation fans should be installed in the kitchen, bathroom, and laundry room. Do not vent fans directly into the roof or crawl space cavities.

2. If electricity is not available, a simple exhaust duct installed over the cook stove and vented through the roof to the outdoors should be provided. The air flow may be controlled by an adjustable damper.

3. Automatic clothes dryers, whether electric or gas heated, should be vented outdoors by an approved vent pipe.

4. Mechanical ventilation is now the norm for new energy efficient housing in Alaska. See CES Publication HCM-01551, Ventilation in Small Houses."

Hermetically sealed interior spaces particularly in tiny homes have the following disadvantages:

- Oxygen levels can get dangerously low.
- Humidity can get trapped inside and cause serious issues. Moisture condensation can quickly build up after cooking, boiling water or taking a shower. Black mold that is dangerous can build up as a result. This humidity should be reduced. (also, moisture venting underlay should be used under mattresses.)
- Appliances that use exterior oxygen should be used rather than those that use indoor oxygen. (Stifled combustion will create deadly levels of carbon monoxide*-detectors must be used especially in tiny homes).

From: < https://tinylifeconsulting.com/properly-venting-a-tiny-house/>: HRV(Heat Recovery Ventilator) and ERV (Energy Recovery Ventilator) offer efficient means to provide balanced ventilation with a ceiling insert ERV. This unit provides a low rate of continuous air exchange. It supplies fresh air to replace exhausted air helping to balance air pressure within the home. It is in-ceiling mounted, as seen in the video, and can be mounted above the shower. In this video the unit is cleverly modified to suck old, moisture laden air out of the bathroom and introduce fresh air into the adjacent living room. [Note: in remote areas, there is no electricity, so solutions should consider passive methods]

If humidity during the winter is an issue, you will choose an HVR. These units use the heat of the old stale air to preheat the fresh incoming air. Humidity is exhausted with the old air. Such units will require the habitat wall to be penetrated: The access holes may be designed and fabricated, including flanges, locating elements, and/or anchor points as desired as long as they meet the required inside diameter specification [get specs from: https://tinylifeconsulting.com/properly-venting-a-tiny-house/] same website also recommend hood, etc.

To replace oxygen without losing heat, a 3-in-1 Air Exchanger unit such as the one in Figure 83, uses a unique, patent-pending heat exchanger to passively heat or cool the air in a small habitat based on the outdoor conditions. Specially designed for tiny houses this size and cost conscious Air Exchanger by Accurasee Mechanical is the most compact single-room heat/energy recovery units. It utilizes neither regenerative matrix nor recuperative plate heat exchangers. However, MINI uses a revolutionary patent-pending breathable-shell shell-and-tube heat exchanger for passive heating in the winter and passive cooling in the summer. There are no electrical heating elements or refrigerant cooling coils in the unit. The heat exchanger is mechanically robust and can prevent frost buildup even in extremely cold climates.

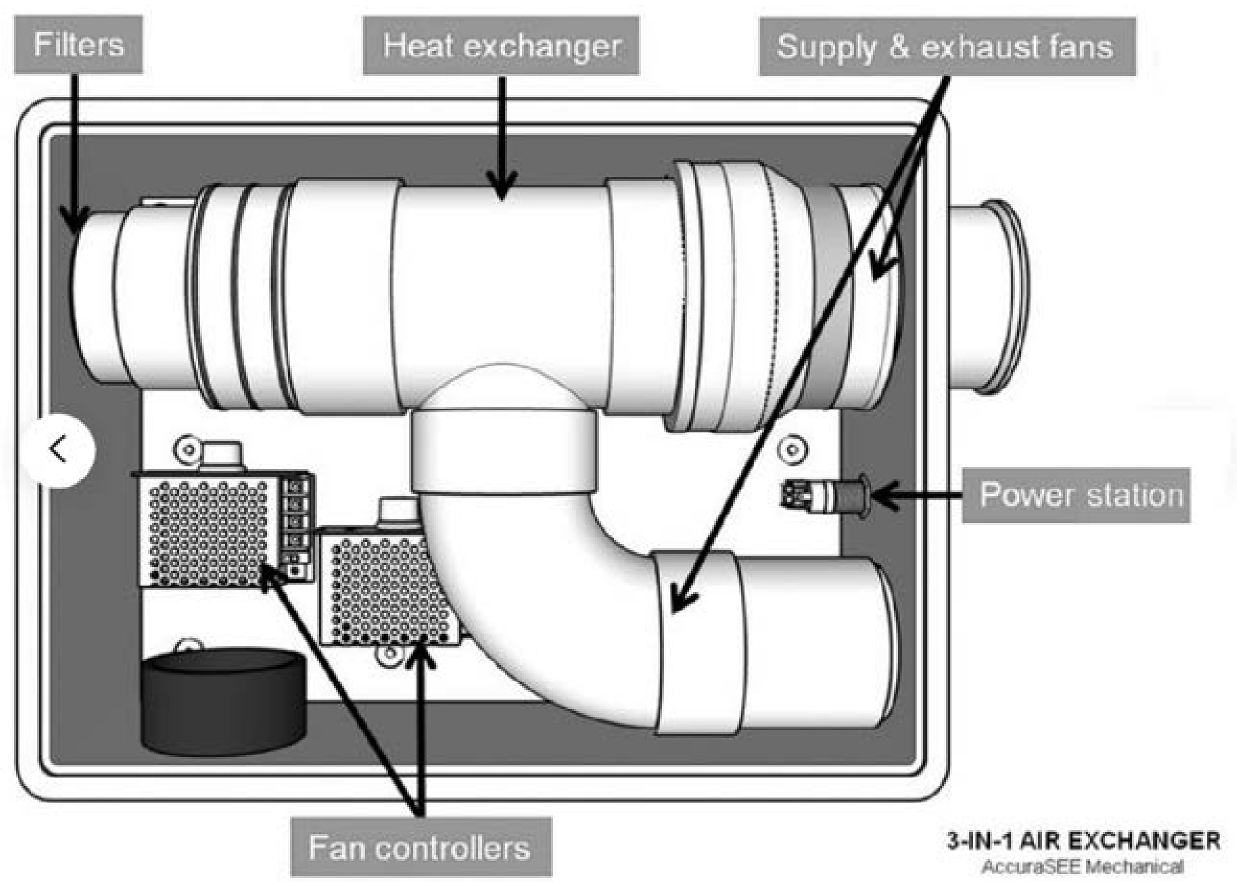


Figure 83. A 3-in-1 Air Exchanger unit [https://tinylifeconsulting.com/properly-venting-a-tiny-house]

Septic Tank:

"All specific an alternative on site waste disposal systems are subject to Department of Environmental conservation regulations and should be installed by a D.E.C. certified installer. Aerobic compost systems exist that are a low water use, very beneficial or alternative to standard septic tank and Leach filled systems." [see: http://www.pacodeandbulletin.gov/Display/pacode?file=/secure/pacode/data/025/chapter73/chap73toc.html&d=]

Closing Discussion of Overall Issues of Interest and Concluding Remarks

This report demonstrates the work done over the past four months during Phase 1 (Feasibility Study) of the XTreme Habitat project. The emphasis of the report is to present a case to justify Additive Construction (3D Printing) technology as an efficient and meaningful mode of construction of habitats in remote areas of Alaska while meeting the goals stated earlier in the *Abstract*.

While there are many more aspects to address such as embodied energy, operational energy, life cycle assessment, cost comparison with conventional wood-frame construction, comparison with offsite option vs. site-built option, comparison of locally sourced material such as aggregates vs shipping such material, the focus of this report is more on architectural and engineering aspects.

Starting with the printing system, the design presented is based on using a Robotic Arm printing system, as opposed to Gantry Frame system. While the latter can also be used, it is less flexible and limited to 3-axis, and more difficult to transport and set up especially in unpredictable landscapes, Our printing system has 6 axes of freedom, it is more agile, more compact, easier to alter and adapt, easy to deploy (folded in transit), easy to assemble, can perform multiple tasks (using tool-changing mechanism), can achieve more complex geometries, can be equipped with compound extensions for arm's reach, and can be raised on a moving base. The flexibility of the 6-axis Robotic Arms systems would enable us to achieve printing the entire structure including an integrated roof and enclosure, whereas the gantry frame system, in the current state of the technology is capable of printing mainly vertical walls. Additionally, while 3D printing of concrete cuts down on the construction time, other parts of the structure such as foundation, roof, insulation, surface finishing, utilities, etc. add to the construction of the entire structure, as in other conventional construction.

The issue of transporting the equipment to a remote site has been considered. A printer system in a Conex Box is being developed that can easily be transported to the site, air-lifted where there is a lack of road infrastructures or trucked if the site can be accessed by roads. Once the Conex is at job site, it can be moved around either using heaving machinery such as large capacity forklift or be mounted on a moveable scissor jack, which also allows the robot to reach desirable heights. We envision the scissor jack can also be shipped as part of the Conex box assembly. The site needs to be relatively level for the Conex to move around the site, so some prior site preparation may be necessary.

While this project has focused on architectural and structural design of a printed concrete habitat in remote Alaska, the important questions of cost effectiveness and rationale still needs to be addressed in detail, but that question is beyond the scope of this feasibility study. Nonetheless, some issues of interest are addressed here. First, we envision that once a Phase 2 project establishes the field feasibility of printing a prototype habitat, scaling up to build a village needs to be addressed. We envision that for such a scale construction, a contractor needs to be engaged that either already has 3D printing systems and is involved in such projects, or a new contractor, e.g., a local contractor, can invest in developing a 3D printing operation unit. We believe that under such a scenario, the investment will be meaningful and hopefully, there will be economic incentives for such a contractor.

The other question of interest has been about whether or not using local rock to crush and make aggregate for the mixture will be more economical compared to just shipping such aggregates. In general, the more local material is used, there will be more saving on transportation cost. However, to answer this question accurately, detailed analysis considering the energy needed to do this task locally vs. from the main source and shipping to the site needs to be considered. Furthermore, besides cost comparison, there are aspects such as embodied energy (LCA) that needs to be considered. Another question of interest about use of local material is whether snow can be melted and used for construction. According to several internet articles, in general, clean white snow is considered good for drinking; accordingly, clear water obtained by melting uncontaminated snow can be considered for mixing concrete.

To further address the issue of local vs. shipped materials, it should be noted that 3D printing companies need to have a mixture design that suits their particular type of printing system. If use of say 50% local aggregate becomes a requirement for a contractor to be eligible for building 3D printed habitats, the printing companies would need to likely adjust available or specified mixture designs to properly work with their systems for printing parameters such as pumpability, extrudability, buildability, open time, speed of printer, pump pressure, etc. Furthermore, the local contractor would need to invest in equipment to crush rocks, sieve, packaging, train workers, and locally ship the material. It seems that even if both options lead to equivalent outcomes, still preparing these locally will be advantageous as it will help the local employment and economy as it starts developing a trained- workforce.

One other aspect of comparison is prefabrication in the shop vs. on-site construction. Modular fabrication of habitat units is certainly an option that is currently used by a few 3D printing companies and that can be evaluated in comparison with site-built option. In the world of conventional cast concrete, it is often advantageous to prefabricate parts or even make the modular units offsite and ship them to the site. The advantages include rapid erection, fewer onsite labor, higher quality construction in the fabrication shop, higher material quality due to the lower onsite labor cost, etc. However, in the newborn world of 3D printing, the difference is that the fabrication shop is at the site, that is, the 3D printer system has much of the benefits of factory prefabrication/assembly, with the advantage that it can be set up in remote areas where normally trucks cannot drive and deliver prefabricated or modular units.

Another issue related to investment by a contractor is what happens after a village development project is completed, and whether or not the contractor will keep the equipment or try to sell them if there is a market. Clearly, this issue is related to economy of scale, and if there would be a sufficient number of units to be built, there could be enough incentives for a local contractor to invest in setting up 3D printing unit of operation. The printing system components such as robot, gantry frame, mixer, hopper, pump, etc., are always in demand (even for use not related to 3D printing) and can be easily sold.

Regarding the special form(s) of the schematic design studies of the 3D printed habitat, it is true that generally we build walls straight and not curved, which could be for the convenience, repeatability, stacking, storage, packaging, and shipping of rectangular components. However, when it comes to 3D printing, one should note that in digital design and Robotic Additive Construction, it does not make any difference to design and/or print straight or curved walls. Furthermore, the advantage of 3D printing is that is can be custom made, yet mass produced, resulting in mass customization, which means, we have a construction system that can produce custom made buildings without added cost.

Considering the facts that we would be building in extreme weather conditions with heavy snow and storms, and using 3D Printing technologies, domed and vault type structure are determined to be ideal. Four different habitat forms were developed for slab on grade and elevated options, but two of them were more suitable for detailed analysis (Models B and D). Between the two, Model D with closed roof seems is the preferred concept as it can be fully printed without the need for a different roof material or system. Architectural design considered different printing options for walls, such as single wall and double walls, the needed insulation type, position, and finish materials. The foundation systems considered include piled system extending in the permafrost zone and slab on grade. Both systems provide for appropriate thermal break to avoid heat transfer to the ground, in particular, permafrost layer. The habitat system that is elevated above ground is a more complex structure, as it includes slurried piles, adjustable jacks on top of piles to compensate any potential settlement due to heaving, printed columns on top of adjustable jacks, arch type structure support, slanting walls closing at roof with the option of having a slab or glass skylight at the top or completely monolithically closed top, which provides a jointless structure. For structural evaluation, deadload, snow load, wind load and seismic effects were considered that determined some of the dimensions for vaulted columns beneath the floor slab, and for the rebars inside them.

Below is a summary of the main outcomes from the study:

a) Presentation of a review of typical residential construction requirements in Alaska permafrost regions
b) Determination of the parameters and factors to consider in design of a habitat for rural regions.
c) Development of strategies for how to consider constraints and requirements for constructing a habitat based on the 3D printing technology.
d) Study of various foundation options and choosing slurried pile system for piled foundation to support elevated structure, and a slab on grade foundation without excavation (solidly raised above undisturbed ground on bed of sand and gravel).
e) The piles can be wooden or tubular steel, but the preference would be wooden piles.
f) Development of finite element modeling and analysis for two of the four designed habitat models and performing structural analysis considering applicable load

combinations for dead, snow, wind, and seismic loads. Based on the results of the analysis, we refined the design parameters for the columns, including dimension and reinforcement requirements.

g) Review and narrowing down the type of pile system to use.
h) Development of a design detail for adjustable jack at the connection between the pile top and the supporting column for the case of elevated habitat option to include jacking option for settlement adjustment.
i) Specification of the option of spray foam insulation for the habitat interior to minimize heat transfer from the building to the ground.
j) Specification of the option of polyurea as the finish material for the exterior and interior of the
k) Specification of the XPS insulation type/thickness and preliminary details of the sand and gravel beds for the foundation under slab on grade.
l) Carrying out tests on received concrete cylinder samples and providing an analysis of the results, which shows significantly lower compressive capacity compared to what is needed to provide the capacities of the structural components.
m) Suggestions for improving the sample preparation to obtain more improved compression capacities.
n) Configuration of printing machine setup and toolpath requirement for field printing.

In Summary, based on this Phase 1 study, it is concluded that the developed schematic designs can work safely under all applicable loading types that were considered. The results show that 3D printing of a habitat of the size and configuration studied is feasible. Applicable and relevant parameters for design, construction, and operation of 3D printing system in remote Alaska areas have been identified and either quantitatively specified or suggested for further follow-up Phase 2 detailed study. Finally, the report addresses some of the issues related to appropriateness of using local materials, conditions for transportation of the printer in the Conex Box and overall justification for using 3D printing of habitats on a large scale.

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APPENDIX B:

Analyses of concrete samples with ingredients and engineering analysis of concrete 3D printed box shaped housing structure

APPENDIX B:

The Additive Construction Laboratory (AddConLab) is a multidisciplinary, collaborative effort between the College of Engineering and the Department of Architecture with a mission to explore various aspects of the use of additive manufacturing at construction scale. It addresses a multitude of issues concerning the design of materials, printing system, toolpath, structure, and building design. The laboratory is housed at Civil Infrastructure Testing and Evaluation Laboratory (CITEL), satellite research facility of the University Park Campus at the Pennsylvania State University.

Website: < https://sites.psu.edu/addconlab/people/>
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Analyses of concrete samples with ingredients and engineering analysis of concrete 3D printed box shaped housing structure

Annex: Report on compressive strength of mortars cast with Alaskan aggregate

Sponsored by: Xtreme Habitat Institute and
the Alaska Housing Finance Corporation

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July 13th, 2021

Xtreme Habitats: Mortar made with Alaskan aggregate

Material testing and analysis to evaluate selection and use of local geologic materials in different Alaskan regions for 3D printing of concrete construction

1. Aggregate preparation

Preliminary testing did not follow strict ASTM requirements, and as such follow-up study was performed, where samples were cast, cured and tested at PennState using ordinary portland cement and aggregate shipped from various locations in Alaska (Figure 2):

A=Anchorage
J=Juneau
F=Fairbanks
C=Control (1 part Portland Cement, 5 parts contractor sand <=3.2mm and 1 part water).

A series of 3 by 6 in cylinders was cast for compressive strength evaluation of 4 concrete/mortar mixtures with Alaskan aggregates, as well as one control mixture with PA non-reactive sand. Compressive strength was tested at 7 and 28 days, two cylinders were tested at each day. The aggregates were prepared by sieving the virgin aggregate series A, J, and F (Figure 1) until desired maximum size of the aggregate was obtained and subsequently washing the aggregate to remove the fines.

Figure1. Photographic documentation of the aggregate; top: in as-received condition, bottom: after sieving to eliminate fraction larger than 4.75mm

2. Compressive strength of mortar samples cast at PennState using Alaskan aggregate

Upon aggregate sieving and washing, a series of mortar samples with water to cement-ratio of 0.45 and 55% of aggregate by volume was prepared. Ordinary portland cement was used. A control series was cast ('C') with local to PA, non-reactive aggregate. Samples were cast into 3 by 6 in cylinders to be tested at 7 and 28 days (note that aggregate preparation reduced the aggregate amount and as such smaller samples were cast). The left-over material from each batch was cast into 2 by 2 in. cubic samples to be tested at 7, 14 and 28 days. The results of 14 days, however, are inconclusive and were omitted in the report. Samples were cured in controlled environment (moist room) per ASTM protocol.

The results revealed that all aggregates resulted in mortars reaching structural strength at 28 days. The average of 2 cylinders and cubes tested along with standard deviation are shown in Figures 2 and 3, respectively. The aggregate sourced in Alaska resulted in slightly lower compressive strength than control aggregate, except for series A verified by compressive strength testing on cubic samples.

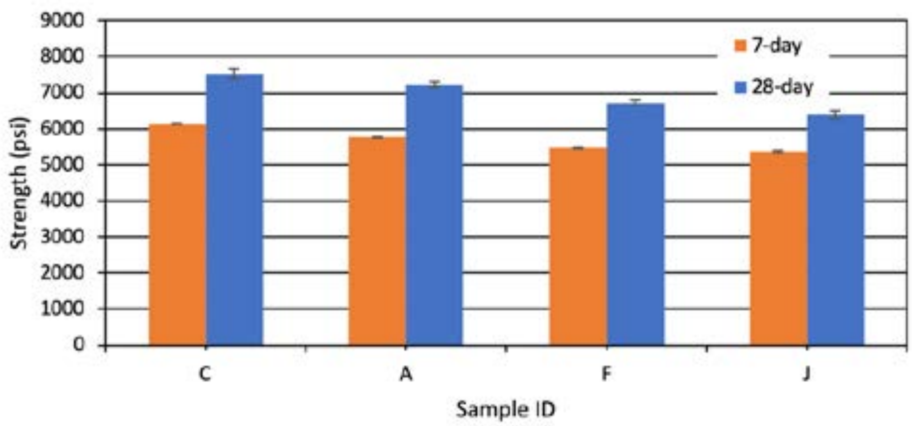

Figure 2. Compressive strength measured at 7 and 28 days on 3 by 6 in cylindrical samples

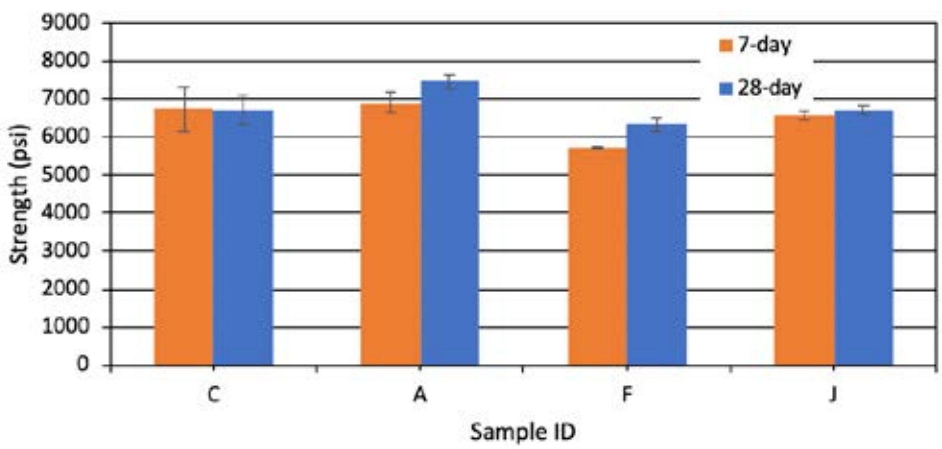

Figure 3. Compressive strength measured at 7 and 28 days on 2 by 2 in cubic samples

All samples failed in a typical manner, as shown in Figures 4 and 5.

Figure 4. Photographic documentation of samples after failure at 7 days

Figure 5. Photographic documentation of samples after failure at 28 days

Closing remarks

All aggregates tested have proven to be a viable option for 3D printing operations in Alaska. Locally sourced aggregates may need to be prepared before printing operations by sieving, adjusting gradation and washing out fines. It is recommended that follow up study is performed to evaluate the aggregates in terms of their long-term performance and durability, as well applications in 3D printed concrete.

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