3D PRINTING SELF-SHADING WALL STRUCTURE WITH EARTH

Enhancing thermal properties in Earthen Architecture through Computational tool path design, inspired by nature & vernacular architecture

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Abstract. Global challenges warrant the rethinking of current housing solutions to provide adequate and affordable shelter for inhabitants. This paper presents an approach for the design and digital fabrication of an earthen wall. The paper reports on a 3-day workshop setting that examined how traditional knowledge of vernacular architecture in combination with biomimicry principles, computational design to enable building-scale additive manufacturing that shade itself and effectively responds to the environment and climate. The study explored innovations in computational tool path design for 3D printing, local material recipe, thermodynamic, environmentally responsive earthen wall, fenestration, airflow, non-planarity and verticality, structure, mass customization, stability, passive design strategies on how to build with local earth materials. In preparation for the workshop, 1:20 glazed ceramic prototypes were 3D printed. The experiments involved sourcing local materials, testing various earth mix recipes, finding an appropriate earth mix recipe for a viscosity that could be 3D printed, calibrating the 3D printer and pumping equipment, and printing the final 1:1 wall segment. The material selected for this study was cob, a mixture consisting of clay, sand, vegetation fibre and water, Locally sourced earth material; no transportation required, hence referred to as km-0 material. The motivation of conducting the research is to increase the sustainability, affordability and durability of construction processes.

Keywords. Vernacular architecture, Hot arid climate, Biomimicry, Cob, Earth materials, 3D Printing, Sustainability, Computational Design, Environmental analysis.

1. Introduction

This paper describes how a prototype self-cooling earthen wall segment was 3D printed

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in a CADDRIA 2022 workshop held in Sydney, Australia. The research study is built on literature on vernacular architecture, historical material recipe; the thermal and structural properties of earth material; biomimicry and fluid dynamics principles, by using computational design and robotic.

2. Background literature

The study involves the following discipline areas: (a) vernacular architecture in hot arid climates and traditional material recipes, (b) performative properties of earth materials, and (c) biomimicry & thermodynamics principles to inform 3D printing processes.

2.1. CLIMATE CHANGE AND CONSTRUCTION ENVIROMENTAL FOOTPRINT.

The 10-year global mean temperature for the period 2013-2022 is estimated to be 1.14 [1.02 to 1.27] °C above the 1850-1900 average (WMO, 2022). This indicates continued climate warming, as noted in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC AR6 WGI, 2021). The AR6 report also highlights an increase in extreme heatwaves, floods, storms, coastal erosion, and wildfires in certain regions.

On a global scale, UNEP (2019) argues that the building and construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO2) emissions in 2018. It is estimated that concrete alone is responsible for 8% of the total carbon emissions caused by human activities (Mokhlesian and Holmén, 2012; Lehne and Preston, 2018; Omer, 2008; Ramesh et al., 2010). Reports by the United Nations and other scholars indicate that the global population is projected to reach over 11.2 billion by the year 2100 (Dyson, 2010), with modeling suggesting that more than 2 billion new homes over the next 80 years are needed. This situation calls for a rethink and the use of alternative and local materials to reduce the environmental footprint of construction."

2.2. VERNACULAR ARCHITECTURE IN HOT ARID CLIMATES.

Research in vernacular architecture in a hot arid climate presents design and material strategies to deal with extreme heat, such as building with earth materials and the use of cooling towers as part of Iran's traditional architecture. The use of earth materials is nothing new to humans. For centuries, vernacular architecture has existed as a method of construction to address the needs of local settlements by using locally and conveniently sourced materials like soil, clay, sand, rock, and timber, in addition to organic local materials such as straw or leaf fibers. Earthen architecture can be found throughout history and all around the globe, and it is estimated that currently about two billion people are living in buildings made of earth material (Keefe, 2005). There is a saying that if something has been relevant once, it is always relevant (Ardalan N, et al. 2015). Vernacular architecture in the city of Yazd (یزد), in central Iran, provides a background on how to build in cob and earth materials with natural cooling (Ahadi, et al., 2009). Yazd was built on the edge of Iran's central desert and is home to a number of traditional earthen buildings. A particular architectural feature visible in the city is the inclusion of cooling towers or wind-catchers (Fig. 1.a). In arid climates, water is a precious resource, and to avoid unnecessary evaporation during transport, Iranians dug underground aqueduct channels, referred to as Qanat (قنات), an ancient system of water supply constructed as a series of well-like vertical shafts connected by a gently sloping tunnel to transfer water (Ahmadi et al., 2012; Angelakis et al., 2016).

The hot air enters Qanat's tunnels underground, loses heat, and then the cooled air is drawn through vertical channels into the basement of buildings. The wind-catchers create a vacuum to remove the used hot air in the building. Wind-catchers are not exclusive to the city of Yazd and can be found in many places around the world. Studies suggest wind-catchers in Yazd are capable of reducing the temperature inside a building by up to 15 degrees Celsius (Hosseini, et al., 2016).

2.3. HISTORICAL COB RECIPIES

Cob mixtures consist of subsoil, fiber (e.g., straw), and water, with an occasional addition of lime. Weismann and Bryce (2006) suggested a generic ratio of water to dry subsoil as 1:5 by weight (20% water, 80% subsoil), while the recommended fiber content is 1-2% by weight. Additionally, Hamard et al. (2016) demonstrated in their extensive review paper on cob that the average proportions of the cob mixture are 78% subsoil, 20% water, and 2% fiber (straw) by weight. The subsoil itself naturally consists of clay, silt, sand, and aggregate. The ratios between these ingredients vary across different sourcing locations. Clay is the main binder in cob mixtures, and testing the subsoil properties is an essential step to determine the right cob formula. The clay content in the subsoil is recommended to be 15–25% (Weismann and Bryce, 2006; Hamard et al., 2016). Harrison (1999) also stated a similar recommendation of 20% clay.

2.4. THERMAL & STRUCTURAL PROPERTIES

Research into the performative properties of earth materials offers valuable insights into understanding the thermal and structural performance of earthen architecture. The utilization of locally available earth material not only has a lower carbon footprint in the manufacturing process but also provides better thermal insulation properties for buildings, leading to lower energy consumption during the operational phase (Abanto GA. et al, 2017).

As an example, in temperate climates, masonry buildings are relatively comfortable without air conditioning. Similarly, in the cold season, the thermal mass of the building serves as a 'heat battery,' gradually releasing stored energy (Yarbrough D, et al., 2019). The use of earth material with low tensile capacity tends to favor certain geometries, such as a dome. There are indications that space and geometrical forms are functions of the structural and thermal properties of the material itself (Ardalan N, et al., 2015).

2.5. BIOMIMICRY & FLUID DYNAMIC

Biomimicry and fluid dynamics knowledge could guide a computational process toward cooling using passive design strategies (Weir, J. 1973; Donghwa S, et al., 2016). For example, termites build their nests with clay, managing a constant temperature for their 'houses' via an air circulation system, much like windcatchers (Korb J. 2013).

Another example is cactus geometries that are optimized to create a self-shading geometry and minimize water loss in hot, dry climates (Bastola, A.K et al., 2021).

2.6. 3D PRINTING

Insights above have the potential to be computerised as an input variable into the computer program to generate appropriate toolpath for 3D printing. The rapid adoption of 3D-printing (3DP) technologies in construction, combined with an increased willingness to reduce environmental impact, has facilitated the use of earth materials for modern building industry [Gomaa, M et al 2021]. Computational tools allow for accurate and considered amounts of material deposition, custom tool path design and nozzle movement [Banda P, et al, 2021]. Such flexibility allows geometry optimisation to achieve a lighter structure and yet fulfils the intended design functionality.

3. Research Question & Methodology

The literature review informed the research question mentioned below.

"How can knowledge of vernacular architecture in arid climates, in combination with biomimicry principles and computational design inform 3D printing processes to design and develop a self-shading, structural wall using local material (0-km)? Using computation techniques, Can 3D printed element achieve verticality, thermodynamics, structure, mass customization & geometry optimisation?"

Figure 1. Images from left to right: (a) Wind catcher in city of Yazd, (b) Crossing tool path sample 3d printed ceramics with various parameter values (Source: Author), (c) Vase ceramic, four components stack up, 120 cm tall.

An Action Research (AR) methodology framework applied to deliver outcomes and answer the research question

4. First set of experiments

To translate the above findings from the literature into a 3d printing process, a series of ceramic objects were printed Experiments conducted were:

(a) An experiment to observe the effect of crossing tool paths resulting in merging two surfaces. A parametric script assigned different heights to each crossing layer. Each layer cut across half of the successive layer of the crossing surface, while at the same time the material was deposited directly on top of the successive layer for the same surface (Successive layer height + layer height), such an approach allowed for the continuity of material to be preserved in both directions, yet merging two surfaces. Fig (2.a)

(b) Printing individual segments of an object and assembling the components once semi-dry by stacking them on top of one another. Such an approach is one way to overcome buckling caused by the nature of the material, which can produce taller objects and also allows for utilisation of prefabrication methodology. The ceramic vase depicted in Fig (2.b) was created by stacking four components on top of each other. Each segment was printed individually, once clay was leather hard, the components were assembled, using a slurry to create one single solid unit, then the clay object was put into the kiln to be bisque (900°Celcius); to create a single unit of ceramic. Later glazing was applied to the object and the object was again put into a kiln (1280°Celcius). Porcelain clay was used in the print. The vase was 120 cm tall.

4.1. CERAMIC PRINTS

Five objects (Scale 1:20) were printed prior to the workshop using terracotta clay. Various values were assigned to defined parameters to confirm the printability of the design and to debug the definition (Fig 2.a.), which followed by the main print. (Fig 3.c.) Clay objects were bisque fired, in the next stage of firing, targeted glaze colouring was applied to the ceramic to enhance the Bernoulli's effect. Channels on the fascia were glazed in black colour to absorb sun energy, the body of the ceramic was glazed in white to reflect back the unwanted radiation. (Fig 3.b) A smoke test confirmed the hypotheses, that warming increases air movement. The printed ceramic object was placed under the direct sun to absorb sun energy, then an incense was lit and placed at the base of the glazed print, and the smoke started to travel through the channels, confirming the hypothesis. The same object did not show this effect without being warmed in the sun. The smoke test experience needs to be repeated in a laboratory setting to produce empirical data. After the first set of test prints, it became apparent the stability of the geometry will increase if the frequency of infill is divisible by the frequency of fascia vertical channels. As a result of such value assignment to the parameters, the connection point of facia elements would be aligned with the infill

Figure 2. Images from left to right - (a) Sample 3d printed ceramics with various parameters value, (b) Failed print, not having a suitable viscosity, (c) Systematic material mixing, (d) Result of radiation analysis used in geometry optimisation

pattern. Another implemented design decision was to alternate the direction of the nozzle movement on every second layer, otherwise the final print might have been skewed in one direction depending on the direction of the print. Such approach will result in more stable printed geometry since the internal forces caused by the plasticity of the material would cancel each other out. Printing these ceramic tiles, one could think of their application in façade cladding.

5. Wall Segment

Here we describe the scope of the workshop project, the stakeholders, and the activities which took place prior to and during the workshop. The workshop took the first step to establish preliminary 3D printing experiments for wall structures and produced a Self-Shading Geometry using natural local materials which can cool itself utilising Bernoulli and Venturi effect, which is analogous to termite nests. Prior to the workshop, a number of large cylindrical objects were printed to understand the required viscosity of the material. It became apparent that the right viscosity was essential for a successful print. (Fig 2.b)

5.1. PROJECT PROPOSAL AND SCOPE

The workshop project was partially sponsored by Narara Ecovillage is located just over an hour north of Sydney. The initial proposed design concept was to 3D print a wall to reach 2.4 metres in height prior to the shrinkage. It was proposed to print the wall in three horizontal segments, then for each segment to be lifted and stacked on top of each other, similar to the concept mentioned in Fig (1c). However due to time and logistical constraints, only the base was completed in the workshop. By creating a task breakdown schedule, it became apparent that there were three major categories of concern to be investigated during the research: materials, machinery and design.

5.2. MATERIAL

A systematic approach was used to find the suitable viscosity for the material. Clay and sand were sourced from a local quarry. Various vegetation fibres such as straw, hemp, and sugar cane were tested. (Fig 2.c) The final recipe for the workshop (by weight) was as follow: 50% sand, 47% clay (abundant by-product from cutting sandstone at the local quarry), 1% hemp, and 2% engineered ball clay used in pottery. Sodium silicate was also added to the mix at the end, using a concentration of 10CC for every 100kg of the final mix, to increase the pump-ability of the material. The hemp fibre was composed of the wooden core of the hemp plant stem.

5.3. MACHINERY

Machinery included: (a) 'Mighty Small 50 Plus/s50 Airless' Cementitious Deposition Pump supplied by 3D potter, and (b) ‘Scara V3 3D’ printer with a build area of 1829mm Diameter Circle surrounding the machine with a Z travel of 1143mm and a belt driven movement system running at a speed of 30 to 100 mm/s. The Scara robot was sufficiently matched to the extrusion rate of the Cementitious pump at a nozzle diameter of 10-17mm. The pump was actuated manually by the operator, using a push button remote attached to the machine by a long cable. Fibrous materials like hemp and straw used in some of our cob test mixes had a tendency to clog and tangle inside the auger of this pump. The Pump requires a natural air seal provided by the mass of material being pumped. This air seal had a tendency to ‘break’ when using ‘tighter’, dryer mixes of cob. This allowed air into the mix, which lead to sporadic bursts of air pressure at the nozzle, and an overly aerated extrusion. Dryer mixes of cob also tended to stop engaging with the auger at times, either completely stopping extrusion, or resulting in under extrusion. (Fig 2.b). Small amount of cooking oil were sprayed on walls of pump's container to prevent mix from sticking to the pump's wall.

5.4. COMPUTATIONAL DESIGN

A parametric definition was set up using the software Grasshopper to model the geometry, run radiation analysis, create tool-path and produce a set of machine instructions referred to as G-code.

5.4.1. Proposed Design

A cross-section of the wall consists of the following three main elements:(Fig 3.a):

(a) Rectangular boundary: defines the functional boundary of the wall section. Defined parameters for the component are as follows: Width, Depth.

(b) Infill pattern: two crossing sine-waves patterns, with a phase difference of π radians or 180 °, inside the rectangular boundary to define an infill pattern of the cross section. The infill pattern serves as a structural element and the frequency can be increased to carry the design's structural load. Two waves are crossing each other using a technique described earlier in the paper (Fig 1.b). The space between the two waves and boundary can be filled up with desired material in later stages of the construction to improve thermal and structural properties of the printed segment. “Frequency of infill” or “Number of cycles” is defined as a parameter in the Grasshopper definition. Amplitude of the waves are defined by the size of the boundary and geometry of infill was calculated using general wave equation:

$$X(t) = A.\cos(2\pi f t + \varphi)$$

(c) Biomimetic vertical channels of the facia: stacking the proposed cross-section on top of another will result in a series of vertical hollow shafts on the surface of the wall, to utilise natural ventilation. These channels are designed to absorb the sun radiation, which consequently will heat up the air in the channels. The thermal stacking effect will rise the hot air through the printed exhaust channels, therefore it is proposed that such geometry can cool itself down. It is important to mention such empirical data has not been collected to measure the cooling effect of the design, however overall the air channels will improve the thermal property & achieve mass customization of the wall segment.

Defined parameters for the component are as follow: “Frequency of vertical shafts” Or “Number of Vertical channel”, “Rotation angle” or “The angle between the centre of the of the projected shaft & normal vector of the wall surface”, Depth of the vertical channels. Some of the other parameters captured in a definition were as follow: (a) Layer height: A function of nozzle diameter; (b) Feed rate: Proportional to the speed on which the arm moves; (c) Extrusion rate: Amount of extruder material per minute; and (d) Wall Height.

5.4.2. Environmental analysis

The final resting location of the wall was confirmed to sit facing North, in the direction of direct sunlight in the southern hemisphere, with direct Sun shining on the fascia of the wall. This decision was particularly important since it had a direct effect on the proposed optimised geometry of the printed wall. An Environmental analysis tool (Ladybug) was used to measure the total amount of radiation received by the northern surface of the wall depicted in Fig 2.d, measuring the self-shading effect of the vertical channels and their effectiveness in blocking direct sun radiation (see Fig 3.a). In the next step, a single objective optimization algorithm (Galapagos) was used to calculate the optimal rotation angles and required minimum depth of the air channels to maximise the airflow effect, by making the channels to absorb the most amount of the radiation. In other words, the vertical channels are the most effective when they cast the most possible amount of shade on the wall's surface. The parametric nature of the study allowed for the radiation analysis to be done on all the possible design options, then the most effective solution was chosen. It turned out that for the north-facing wall located in Sydney latitude, the optimal rotation angle of the vertical channels to block the hot summer afternoon is 120° clockwise, parallel to the surface of the wall. The analysis was conducted on a set of all the possible angles with 15° intervals {15°, 30°, 45°…, 160°,175°}, and best performing design was chosen and printed. Chosen angle depicted in figure 3.a with orange colour.

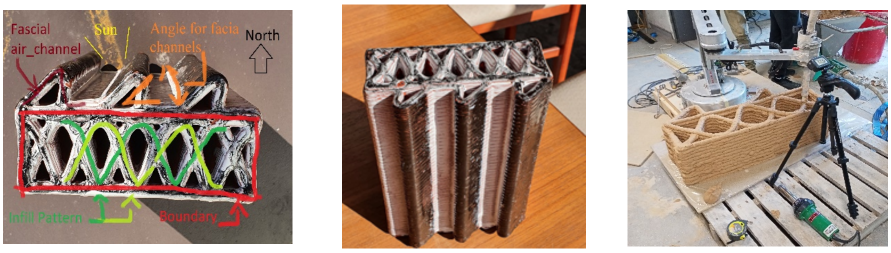

Figure 3. Images from left to right - (a) Crossing section of wall component, (b) Glazed ceramic object, shading effect is visible, (c) Final Print, reaching 40cm height

6. Outcome

We report on the first set of 3D printing ceramic prototypes (scale 1:20), Set of large cylindrical objects (fig 2b), followed by the printing of large structural wall segment prototype, using earth material (scale 1:1). It was noted that the air humidity and sunlight have an effect on the solidification rate of the material. Vertical voids within the geometry can enhance the airflow to speed up drying time by use of air compressor to blow the air into the vertical cavity channels. The following values were assigned to parameters: Boundary box dimension 120cm x 40 cm, the depth of Vertical channels 25 cm, Rotation angle 30°, infill frequency 2, Fascia frequency 2. Print achieved 45cm verticality, (45 cm tall).

We present the following novel contributions in our work: Verticality, the utilization of locally sourced materials (km-0), pump-able material recipe, geometry optimization, radiation analysis to maximize self-shading effects, an innovative tool path design alternating every second layer, the implementation of a parametric infill pattern, exploration of crossing layers for improved structural strength and thermal properties, incorporation of vertical channels for enhanced air ventilation or service ducts, strategies for mass and weight reduction and the exploration of stacking printed clay components to create a unified, load-bearing structural wall.

7. Next Steps and Conclusion

By incorporating local earthen 3D-printed elements alongside techniques such as rammed earth, ceramic facades, and utilizing timber for tensional control, there is potential to create sustainable and affordable housing solutions resistant to elevated temperatures. The objective is to extend the research into printing other building elements, such as roofs, aligning with the goal of constructing with km-0 earth materials to reduce costs and environmental footprint. Precise material deposition allows for non-planer, optimised geometry to enhance thermal performance of the buildings.

The next steps involve testing the material against Australian building codes for strength and durability. The mechanical printing system will be modified with a retraction system to control material flow, triggered via G Code instructions and a digital interface. This enhances usability during prototyping. Larger robotic systems are planned for scaling 3D printed parts. Additionally, The prototype was exhibited and then moved to the Ecovillage to observe the weathering effect on the wall, promote the technology, and support the research.

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