Chapter 2

Additive Energy: 3D Printing Thermally Performative Building Elements with Low Carbon Earthen Materials

Alexander Curth*, Eduardo Gascón Alvarez,
Lawrence Sass, Leslie Norford and Caitlin Mueller
MIT Department of Architecture

INTRODUCTION

Global temperatures continue to rise, driving both rapid urbanization and a resultant widespread need for low-carbon impact, thermally performative, and rapidly scalable building technologies. Solutions combining locally available materials and advances in computational building energy modeling and fabrication offer a potential path toward effective and equitable decarbonization. Additive manufacturing is an emerging technology that enables designers to leverage complex geometry at a low-cost to embed performance across scales. 3D-printed buildings have now been constructed on every continent except Antarctica, and both NASA and SpaceX rely on 3D-printed heat exchange manifolds and

---

*For Correspondence: curth@mit.edu

functionally graded structural lattices in their rocket engines (Figure 1). To date, few studies have addressed the potential for regulating heat in buildings with additively manufactured elements, in part because of the considerable expense of conventional printing systems and materials. We present a set of novel design methods and building systems from the scale of a brick to the scale of a wall utilizing a combination of simulation-driven design and additive manufacturing with earth and clay. By leveraging materials readily available in all climates, bespoke, simulation-driven building elements could be manufactured from these low or no-cost materials to create performative, low-carbon buildings. By providing a methodology for material and fabrication-aware energy simulation for additive manufacturing, we provide a scalable groundwork for future studies across climates and local building requirements.

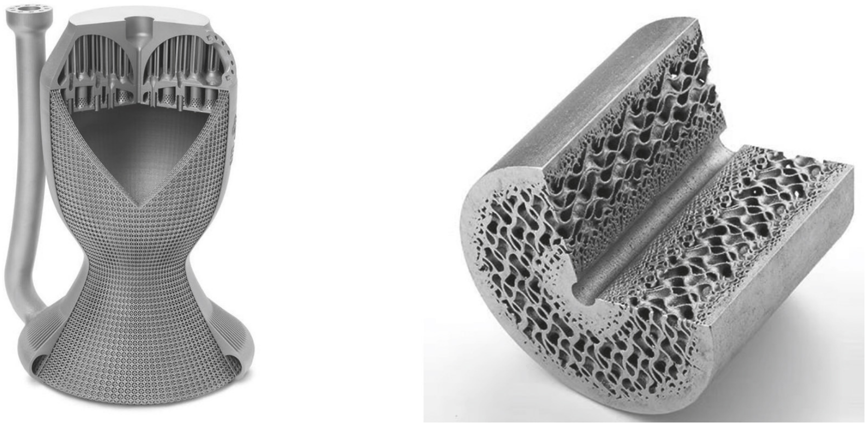

Figure 1 High-performance heat exchangers have been 3D printed for aerospace applications including cooling and temperature-regulated fuel injection, demonstrating the potential for highly functional and hierarchical geometric complexity in a monolithic, monomaterial, unit. (Left image – SLM, Right image – Hyperganic).

IMPACT

As the impact of climate change on cities continues to grow, reducing the cost and time required to produce comfortable and equitable housing is becoming increasingly urgent. Extreme heat events overtax and break urban energy infrastructure from Delhi, India to Houston, USA, resulting in the failure of cooling systems and creating widespread health emergencies. New housing must not only be affordable, it must also include effective means of passive energy regulation, a key design factor in many cultures' vernacular building systems, which has now been replaced with thermally inefficient structures that rely entirely on air conditioning to keep occupants cool. In addition, building under insulated structures without passive thermal comfort performance results in significant embodied energy impact from air conditioning, further exacerbating climate change. At the same time, much of the rapid housing construction happening in cities around the world is concrete, a particularly inefficient and high-carbon material responsible for 8% of global carbon emissions each year (Röck et al. 2020). In this study, we ask if there are broadly scalable methods for additively manufacturing low-carbon, climate-specific architecture that are thermally and structurally performative for housing. We then demonstrate that performative, hierarchical building elements can be produced from extremely low-cost, low-carbon materials like earth using increasingly available 3D printing tools.

BACKGROUND: OPPORTUNITIES AND CHALLENGES OF 3D PRINTED EARTHEN CONSTRUCTION

Additive Manufacturing for Construction

The automation of buildings to reduce cost and improve performance has captured the imagination of engineers and inventors since mid-twentieth century. In 1939 William Urschel created the first "Wall Building Machine," a device driven by an analog mechanical cam system to continuously slip-form concrete walls. Over the course of the next decade, Urschel built a series of buildings, including a two-story structure still in use today, eighty years after its construction (Curth 2022). The final iterations of the Wall Building Machine included integrated reinforcement and were used to fabricate structures with complex floorplans and apertures which are still occupied today, overcoming many of the challenges present in the contemporary industry of Large Scale Additive Manufacturing (LSAM).

It would be nearly forty years before the terms "3D printing" or "additive manufacturing" were coined to describe the work of Hideo Kodama (the inventor of selective laser sintering-SLA) and later Chuck Hull (the inventor of powder bed printing) (Kodama 1981, Hull 1986). Despite Kodama's first 3D print being a miniature scale model of a traditional Japanese house, it would not be until the 2000's that additive manufacturing technology would be engaged for architectural scale applications by Berok Khoshnevis (Contour Crafting) and Enrico Dini (D-shape, large scale powder bed printing) (Khoshnevis 2004, Dini et al. 2006). Both Koshnevis's and Dini's approaches have been engaged to make buildings, which, like Urschell's prototypical structures do include some investigation of the integration of mechanical, electrical, and plumbing as well as structural performance and the inclusion of voids to be filled with conventional insulation.

Khoshnevis's approach, Contour Crafting (CC), is the most widespread contemporary method of LSAM. To produce an object, geometry is discretized into layers (contours) which a computer-controlled machine then follows, extruding paste pumped or otherwise supplied to an end effector. Essentially Fused Deposition Modeling (FDM), CC is typically used to make shell structures that can be extruded in a continuous toolpath. To produce more complex geometry with infill, support structures or topologically distinct regions, precise control of extrusion is required to achieve smooth retraction and travel moves. The most advanced systems available today can have the same functionality as a desktop FDM printer, so long as they are supplied with a highly characterized material with consistent properties to facilitate retraction, flow control, and stable mechanical behavior after extrusion. Functionally, this indicated that geometry of similar complexity to the rocket engine components in Figure 1 could be fabricated at an architectural scale if the design tools existed and material properties could be calibrated effectively.

Additive manufacturing allows designers and engineers to create complex geometry quickly and at low cost in a wide range of functional materials. Unlocking this potential for the architectural scale is a growing area of research. Projects in industry and academia have explored myriad materials for architectural AM, including mortar, earth, clay, plastic, and metal. The most common large-scale 3D printed structures are single-story houses constructed from quick-curing mortar. While these structures demonstrate exciting geometric potential, and in some cases, are produced faster than conventional methods would allow, their environmental impact is significantly higher than traditional building systems (Roux et al. 2022, Tinoco et al. 2022). Lower carbon 3D printing systems utilizing earth and clay offer a promising alternative (Curth et al. 2020). The widespread availability of earthen materials suitable for construction makes them a compelling choice for globally scalable AM systems; however, calibrating an un-engineered material like local soil presents unique challenges, including extrusion consistency, shrinkage, and variable mechanical properties. This study presents 3D printed prototypes illustrating thermally performative building elements and 3D printed at high precision with locally sourced earth and clay. Our novel integration of energy modeling and design for additive fabrication allows us to create climate-specific building systems with exceptionally local low-carbon materials. The outputs of our study are designed to be readily adoptable in existing construction practices through adherence to local building energy standards.

Thermal Performance and Resiliency to Heat

Earthen construction has been used traditionally in temperate and hot desert climates due to its high thermal mass properties, allowing buildings to dampen indoor air temperature fluctuations and avoid excessive hot indoor temperatures (Olgyay 2015). In the current climate crisis context, thermal mass is often revisited as an effective adaptation strategy thanks to the aforementioned peak-reduction effect and its ability to delay in time the consequence of disruptive events such as heat waves or power outages (Zhang et al. 2021). Recent studies have also investigated the ability of earthen assemblies to regulate the moisture content in indoor spaces, a critical aspect when evaluating occupants' thermal comfort conditions (Ben-Alon and Rempel 2023). Moreover, buildings with a high time constant value (i.e., sufficient interior thermal mass and adequate exterior insulation) allow for implementing pre-cooling and pre-heating control strategies that prevent the electric grid from being excessively loaded during high-demand periods, an increasing concern as cities rapidly electrify (Reynders et al. 2013). These multi-domain benefits highlight the importance of finding low-carbon ways to apply thermal mass in buildings as a climate change mitigation and adaptation strategy.

To achieve this, this work investigates how additive manufacturing can further improve the thermal performance of earthen construction (either monolithic walls or discrete blocks) through a context-specific design approach. The fabrication freedom AM provides allows for the precise allocation of the printed material, optimally varying its thermal properties based on the boundary conditions at each surface and the heat flow dynamics within its structure. Yet, recent developments in 3D printing have focused almost exclusively on the elements' structural performance and printability, seldom evaluating their impact on the buildings' energy efficiency and indoor thermal comfort conditions (Pessoa et al. 2021). Existing studies on the thermal performance of 3D printed structures investigate, in most cases, ways to reduce their thermal conductivity through, for example, the design of lattice structures with closed air cavities (Dielemans et al. 2021) or the addition of low-conductivity materials into the mix design (Ma et al. 2022). Other bioclimatic factors have been explored through the construction of prototypes, such as optimal ceramic shading systems (Bechthold et al. 2011) or adaptable heat storage (Sarakinioti et al. 2018). However, very few of these have focused on the abovementioned passive thermal mass performance of earthen buildings (Figliola and Battisti 2021).

There is, therefore, an existing research gap in the design of 3D-printed earthen buildings for optimal and holistic thermal performance while incorporating considerations on material properties, fabrication constraints, and overall environmental impact. As highlighted by a recent review on the heat-moisture properties of 3D printed walls (Li et al. 2023), the combined study of their material and thermal properties opens a promising and relatively unexplored field of research on the multi-functionality aspect of these systems. In this work, we focus on earthen wall systems at a macroscopic scale, exploring printable geometries that maximize the heat resilience benefits earthen materials provide as a low-carbon and accessible resource.

Research Opportunity

Digital fabrication for architecture has been an active area of academic research for over 20 years; however, the level of adoption by the construction industry is low compared to other manufacturing areas. Digital fabrication is now nearly ubiquitous in the automotive and medical industries while in construction CNC or 3D printed components are only seen in experimental or exceptionally high-end projects like museums or stadiums (Schniederjans 2017). Translating architectural digital fabrication research to the construction site requires acknowledging the tight margins and resulting high risk, associated with adopting emerging technologies for new buildings (Hossain et al. 2020). By using the exceptionally low-cost material of un-engineered soil we aim to create an accessible advance in building technology that allows for the widespread construction of affordable, thermally performative structures. While earth as a building material has critical limitations, strength, and durability when compared to higher-cost materials like concrete or timber, it is available at nearly every building site in the world and, when paired with simulation-driven design, can be shaped into performative geometry across varying climates and programmatic needs. This work aims at testing and expanding these ideas through a novel computational design framework and the prototyping of two earth-based construction systems.

ADDITIVE ENERGY METHODOLOGY

Additive Energy is a novel design-to-fabrication method that combines digital fabrication, material efficiency, and thermal performance in a holistic and streamlined framework. We use our research site, Santa Barbara, as both the source of our earthen material and the climate around which we designed the prototypical systems demonstrated in the following pages. These include the design of thermally performative wall systems ranging from human assemblable, fired ceramic bricks to raw earth walls 3D-printed on-site at the super-meter scale. We investigated the potential and challenges of both systems for use in residential construction. To do so, we created an optimization loop, linking material and fabrication constraints with design parameters (Figure 2). A thermal analysis then drives the geometry optimization itself to produce an output that balanced material efficiency and thermal performance within the fabrication constraints of our large-scale 3D printing systems.

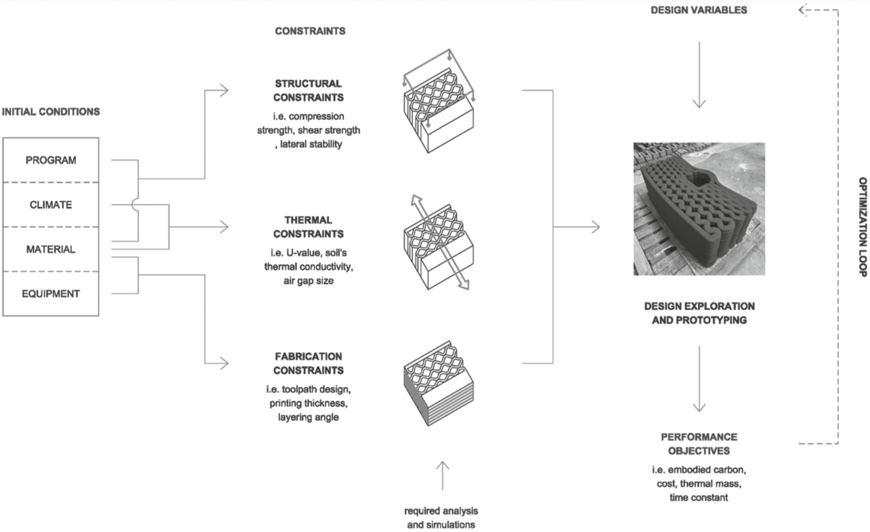

Figure 2 Programmatic and climatic conditions are directly incorporated into a material and fabrication-aware digital construction system.

GEOMETRY DEFINITION AND FABRICATION CONSTRAINTS

Our design optimization methodology balances code-compliant thermal performance with geometries that can be successfully 3D printed at scale with raw earth. To further improve the accessibility of our designs, we constrained them to continuous geometries that do not require expensive in-line valve systems to stop and start extrusion. We use a flexible tool pathing strategy that facilitates both the production of air pockets of varying size throughout a wall section for insulation and solid areas for thermal mass with repeating waveforms of varying frequency and amplitude. Many other geometries exist that could be used to produce a cellular structure for insulation; however, after testing randomly distributed cells, hexagon, circular, and rectilinear void patterns, we settled on a wave-like pattern that facilitates close control of void size and relative position (Figure 3). By controlling the position of adjacent voids, we could adjust position crossing from the exterior to the interior edges of the wall system, tuning its thermal conductivity for performance.

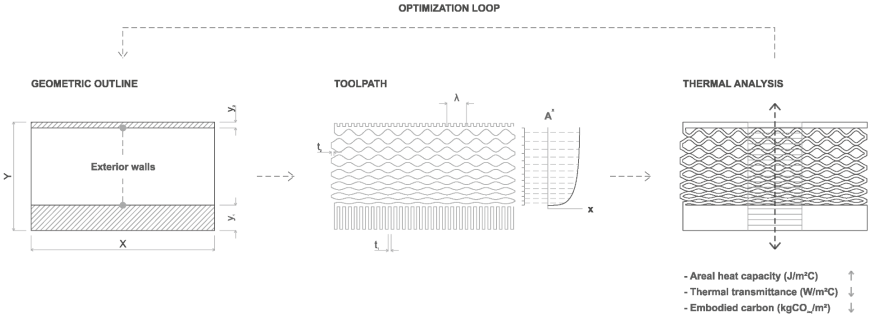

Figure 3 A simple wavelike tool pathing strategy facilitates a thermal optimization loop that is inherently fabrication aware.

Figure 3 shows the parametric model used in this work to generate the different wall and block geometries. As observed, given an initial geometric outline, the workflow generates (i) a printable toolpath and (ii) a continuous surface for thermal analysis. While some input parameters are fixed based on fabrication and material constraints (such as wall thickness t_1 or total depth Y), others become variable parameters input of the mentioned optimization loop (inner wall thickness y_1 or the wave amplitude λ, for example). The metrics U and κ (described in the following section) are combined into a single time constant τ objective and compared against the total embodied carbon in order to understand the trade-offs between thermal performance and material quantities.

Thermal Analysis

Quantifying the thermal performance of geometrically-complex elements such as the ones presented here is a challenging task, even with existing modern simulation methods. Building Energy Modeling (BEM) engines such as EnergyPlus or TRNSYS typically simplify buildings as prismatic objects with one-dimensional heat flows and, as a result, fail to capture the effects of shaping the elements' surfaces or inner structures. On the other hand, it is possible to characterize the thermal properties of shaped components through numerical methods such as Computer Fluid Dynamics (CFD) or Conjugate Heat Transfer (CHT), yet at the expense of high computational costs and an often slow meshing process. The work presented here alternatively uses analytical models based on first principles and fundamental heat transfer theory as a fast and accurate evaluation tool tailored for early-stage design processes that allows iterating across large numbers of options. While still not fully-validated, early tests show high accuracy between the presented analysis method and their equivalent CHT simulations (2–10% error).

We specifically focus on the analysis of two metrics that allow characterizing of the steady-state and dynamic thermal behavior of shaped building components: thermal transmittance U (W/m^{2}C) and areal heat capacity κ_{in} (J/m^{2}C). The former, also defined as U-value, is a well-known measure of the insulation properties of a given envelope assembly typically prescribed in building codes. This work proposes computing the U-value by discretizing a given geometry into two thermal resistance circuits (one in-series and one parallel as upper and lower bounds, respectively) and calculating a weighted average between both. As a result, the method accounts for the two-dimensional heat transfer processes intrinsic to voided walls and roofs with complex inner structures. The second metric, the areal heat capacity κ_{in}, expresses the component's thermal mass ability as the periodic heat flow that flows into its internal surface through a 24 h cycle. It is computed by applying the standard ISO 13786 for the dynamic thermal performance of building components (ISO 2007). Both metrics are finally synthesized into a combined time constant value $\tau(\kappa/U)$ that captures their combined benefits: as τ increases, the component's ability to dampen and time-shift indoor temperature fluctuations increases.

RESULTS

The following pages present an in-depth study of two shaped building elements with homogenous thermal properties. Two different scales – a discrete brick and a continuous wall – are analyzed with two different earth-based materials – clay and soil – to demonstrate the applicability of the ideas and methods presented in the previous section. The proposed building systems are specifically designed for the climate and available local materials in Santa Barbara, California. This coastal city has a warm-summer Mediterranean climate – zone CSb according to the Köppen-Geiger classification (Beck et al. 2018) – with large diurnal swings and average temperatures that fall within comfort ranges during most of the year. These conditions make thermal mass an ideal passive cooling strategy to explore in the context of low-carbon architecture.

Additive Block

Multi-cellular clay blocks are an increasingly popular solution in masonry construction thanks to their improved thermal transmittance values, allowing for a reduction (or, in some cases, total substitution) of conventional insulation materials such as mineral wool or extruded polystyrene. This system has been implemented as an envelope solution in contemporary low-energy buildings, more noticeably in the 2226 office building designed by Baumschlager Eberle (Maierhofer et al. 2022). Here we investigate the possibility of further improving the thermal performance of multi-cellular clay blocks at a minimal material cost by leveraging AM technologies and shape optimization methods. This geometric exploration is conducted through a multi-objective optimization (MOO) process based on the parametric model described in Figure 2 for given material properties (medium fire stoneware clay) and fabrication constraints (4 mm printing nozzle and fixed 15 cm brick depth).

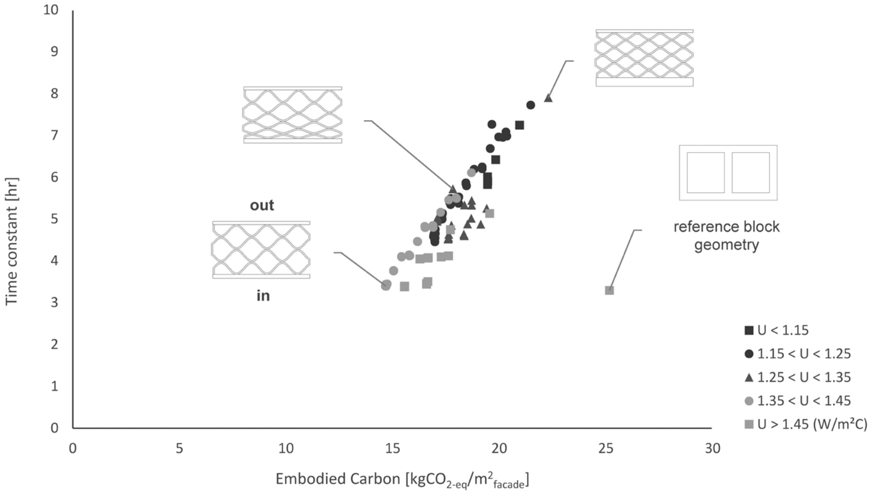

Figure 4 The mass customization inherent to the AM process facilitates a gradient of climate-specific designs.

Two objectives are defined: (i) minimizing the embodied carbon per square meter of the facade and (ii) maximizing the described time constant metric τ, which accounts for the heat capacity and the U-value simultaneously. Figure 4 illustrates how, as initially expected, both metrics counteract each other: adding more material into the brick's inner structure improves its time constant – increasing its storage capacity and number of air pockets – at the expense of a higher embodied impact. The resulting Pareto front reveals a spectrum of sub-optima solutions that, in all cases, have lower embodied carbon (up to 44%) and higher time constant (up to 139%) than a standard reference brick with two rectangular voids. These results highlight the importance of material distribution and geometry optimization in achieving lightweight solutions with enhanced thermal performance. As observed in Figure 4, the obtained bricks with higher time constant values present a gradient in their void structure, with smaller air pockets on the brick's inner side (increasing its internal heat capacity κ where it is more needed) that gradually become larger as they approach the outer side (reducing the needed material).

The fabrication of this optimized brick serves as an opportunity to investigate the inclusion of additional thermal features as a further step toward multi-functionality. In this case, an outer shell is attached to the element's exterior face to provide shade, minimizing the heat gains through solar radiation and providing a ventilation chamber for heat dissipation. A minimum opening area of 50 cm^2 for every meter of brick and a gap size of 20 mm is ensured, following existing façade design guidelines (Herzog et al. 2012). This ventilation chamber is achieved by tilting the outer shell (in this case, with an angle of 8°) vertically, providing an effective water-proofing layer similar to rain screens in ventilated facades. Figure 5. shows the printing process of one design iteration through a continuous toolpath that includes interior thermal mass, insulation, solar shading, and brick interlocking.

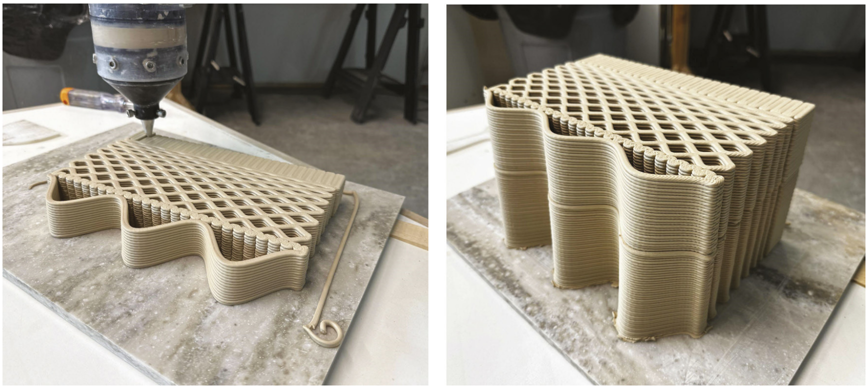

Figure 5 A 3D-printed ceramic block contains a multitude of thermal comfort functions in a monolithic unit; solar shading, insulation, and thermal mass. Manufactured to standard extruded block sizes, this prototype can be assembled with common practice masonry methods.

Additive Wall

The second case study focuses on designing and prototyping multi-functional earthen walls as a low-carbon, local construction method. From a thermal point of view, this research aims at improving the thermal mass and insulation properties of earthen walls through geometric modifications on their internal structure. Unlike traditional monolithic systems, AM allows for fabricating wall components with intricate geometries, resulting in longer heat conduction paths and embedded air pockets that provide high insulation at zero cost. The opportunity then becomes to leverage these strategies to design envelope solutions that meet the energy efficiency standards for the specific context of Santa Barbara. Wall geometries are generated using the previously presented parametric model, accounting for the wall's fabrication constraints and local soil's material properties. More importantly, we define a minimum printing thickness of 3 cm, given the larger nozzle needed to pump the soil mix, and a total wall depth of 50 cm.

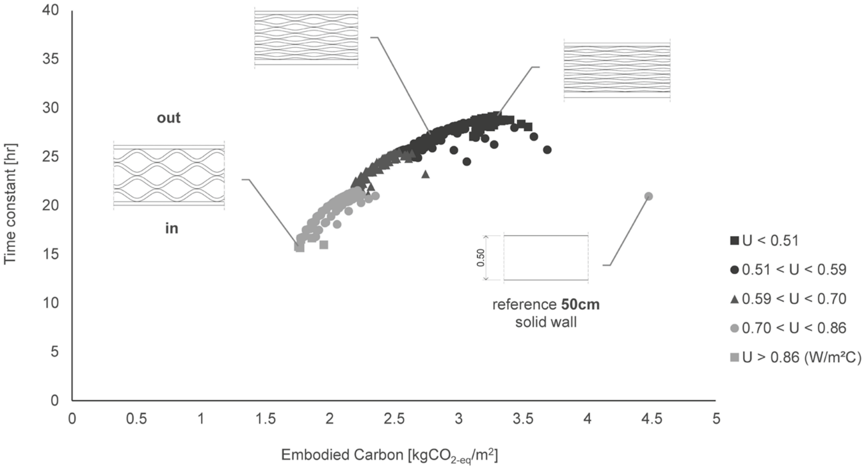

Figure 6 The obtained Pareto allows for selecting designs with minimal embodied carbon for a given target time constant value (which defines the wall's ability to dampen indoor temperature fluctuations).

A MOO process is conducted, once again, to maximize the time constant and minimize the embodied carbon. Figure 6 shows the obtained results. As observed, the shaped wall patterns achieve significantly higher time constant values (up to 40%) with reduced embodied carbon emissions (at least 27%) relative to a reference 50 cm solid wall. These results are particularly relevant from a heat resilience perspective, as they unlock the possibility of designing envelope systems that dampen indoor air temperature fluctuations more effectively and provide a slower response time to extreme heat events. At the same time, the *U*-value is improved drastically across all geometries, reaching, in most cases, values that comply with many of the geographic zones defined in the ASHRAE energy standard 90.1 (ASHRAE 2016). For the specific climate of Santa Barbara (zone 3), designs with *U*-values lower than 0.59 W/m²C are sufficient for wall assemblies. Other formulations of the MOO problem could include this condition (*U*-value < 0.59 W/m²C) as a constraint, ensuring that the process generates code-compliant designs exclusively.

A Pareto-optimal design was printed along a curved wall to test the system's ease of fabrication, paying attention to shrinkage issues during the drying process and dimensional stability. These early tests revealed the suitability of including expansion joints when printing long segments of walls. Further, the toolpath included the formwork for casting a concrete column as a main vertical structural element (Figure 7).

This solution proved the suitability of adding structural reinforcements into the wall with a continuous "insulation layer" that avoids any possible thermal bridge.

Figure 7 Raw earth walls can be 3D printed to climate-specific geometric configurations of thermal mass and insulative voids. Here a 1 × 0.5 × 0.5 wall section demonstrates the functional layout of material for thermal performance in Santa Barbara, California, as well as integrated formwork for a reinforced concrete column.

DISCUSSION

Low Carbon Thermal Comfort and Fire Resistance

The enhanced thermal performance of both systems responds to three phenomena: adding air pockets for insulation, longer thermal conduction paths, and the optimized distribution of materials across the wall section for thermal mass purposes. Combining these concepts with a simulation-informed optimization loop allowed us to quickly produce a climate-specific set of solutions at multiple scales, a brick, and a wall section. Both prototypes embody contemporary advances in building energy design while also being exceptionally low carbon and materially efficient. Unlike conventional, discrete building systems of hierarchical elements (rain screen, insulation, vapor barriers, structure), our system embeds necessary functions in a monomaterial fashion, is quick to fabricate, and is generally independent of the complex material supply chains of modern construction. The key takeaway from our study is that a readily accessible, low-cost, low-carbon material can be transformed into a highly performative modern building element through additive manufacturing for a wide range of climates.

In the specific case of Southern California, these prototypes not only respond to a need for passive thermal comfort, but to a growing demand for architecture that is both low embodied carbon and fire resilient. As climate change exacerbates California's annual cycle of wild fires to point of widespread urban impact (Radeloff et al. 2018), new building systems are required to minimize future urban fire risk. Common practice today involves rebuilding burned homes with concrete, a material that adds to the climate impact driving an increased wildfire season. Offering an energy efficient and thoroughly fire resistant alternative could make for greater urban fire resilience.

Future Work

The key questions resulting from this work are focused around scalability, both in terms of the printing systems used and industry/governmental willingness to adapt to a radical new way of building. Unlike conventional earthen building systems like rammed earth (pisé) or Compressed Earth Blocks (CEB), the prototypes created in this study have the potential to require minimal labor to fabricate at the architectural scale, opening new opportunities for the implementation of earth architecture.

Over the past decade, a number of 3D-printed mortar wall systems have been added to international building codes (ICC Digital Codes 2021). However, it is the inherent advantages of 3D printing for construction that make it difficult to standardize. Different companies use a wide range of proprietary materials, validation software, and mass customizable geometries, making the technology somewhat difficult to fit into existing codes or engineering standards. Our work addresses this challenge through direct and rigorous simulation and testing of a given material.

In addition to challenges of policy and industry perception, many technical as well as Life Cycle Assessment (LCA) aspects of additive energy design remain to be explored. The next steps in the development of both the block and the wall system are laboratory tests of multiple samples to determine the thermal conductivity and time constant of the dried and/or fired prototypes to calibrate the models described to the specific material properties of locally sourced earth and clay. Increasingly complex geometries could also be developed to further reduce the thermal conductivity of what are essentially earthen metamaterials (a single material with varying characteristics). Furthermore, the energy performance of novel 3D printed building systems could also be balanced with other critical metrics, such as mechanical performance. Figure 8 shows an early test by the authors of a closed-cell, ceramic metamaterial designed to insulate while providing a structural building unit. As geometric complexity increases so do the challenges of simulating the behavior of a given system, making the space for further research broad.

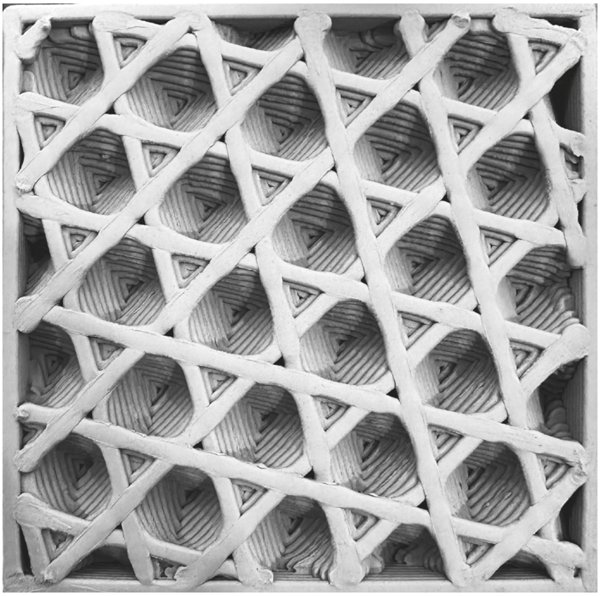

Figure 8 A ceramic or earth cellular solid can be functionally graded and parameterized to balance thermal and structural performance, creating a highly functional building element from one of the world's most readily available low-carbon materials.

CONCLUSION

In this study we present novel methods combining thermal simulation, optimization, and low carbon 3D printing at an architectural scale. The result is a series of prototypes which demonstrate potential for the creation of wall systems that are low carbon, thermally performative and quick to produce with low cost, locally sourced earthen materials. In addition, the Additive Energy methodology is parameterized to allow for the production of climate specific geometry, balancing insulation and thermal mass as needed. Most critically, these systems are compared to local thermal and structural requirements, offering the first steps in a path to industry adoption and ultimately a reduction of the carbon impact of future construction.

ACKNOWLEDGMENTS

Thank you to Clay Studio Santa Barbara and LYNDA Labs for providing space to conduct these experiments and the MIT Programmable Mud Initiative for providing materials and equipment.

REFERENCES

Appendix AW 3D-Printed Building Construction. 2021. International Residential Code (IRC) | ICC Digital Codes. 2021. ICC Digital Codes. https://codes.iccsafe.org/content/IRC2021P2/appendix-aw-3d-printed-building-construction.

ASHRAE, ASHRAE Standard. 2016. Standard 90.1-2016; Energy Standard for Buildings Except Low Rise Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.: Atlanta, GA, USA.

Bechthold, M., King, J., Kane, A., Niemasz, J. and Reinhart, C. 2011. Integrated environmental design and robotic fabrication workflow for ceramic shading systems. pp. 70–75. *In*: Kwon, S. (ed.). Proceedings of the 28th ISARC, Seoul, Korea. International Association for Automation and Robotics in Construction (IAARC). https://doi.org/10.22260/ISARC2011/0010.

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A. and Wood, E.F. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data 5(1): 180214. https://doi.org/10.1038/sdata.2018.214.

Ben-Alon, L. and Rempel, A.R. 2023. Thermal comfort and passive survivability in earthen buildings. Build. Environ. 238: 110339. https://doi.org/10.1016/j.buildenv.2023.110339.

Curth, A., Darweesh, B., Arja, L. and Rael, R. 2020. Advances in 3D printed earth architecture: On-site prototyping with local materials. pp. 105–110. *In*: BE-AM: Building Environment Additive Manufacturing. Damstadt.

Curth, A. 2022. Slip forming to construction 3D printing: the early history of large-scale additive manufacturing. ICI Journal. 23: 16–20.

Dielemans, G., Briels, D., Jaugstetter, F., Henke, K. and Dörfler, K. 2021. Additive manufacturing of thermally enhanced lightweight concrete wall elements with closed cellular structures. J. Facade Des. Eng. 9(1): 59–72. https://doi.org/10.7480/JFDE.2021.1.5418.

Dini, E., Nannini, R. and Chiarugi, M. 2006. Method and device for building automatically conglomerate structures. World Intellectual Property Organization WO2006100556A2, filed March 16, 2006, and issued September 28, 2006. https://patents.google.com/patent/WO2006100556A2/en.

Figliola, A. and Battisti, A. 2021. Informed architecture and clay materials. Overview of the main european research paths. pp. 47–72. *In*: Figliola, A. and Battisti, A. (eds). Post-industrial Robotics. Springer, Singapore. https://doi.org/10.1007/978-981-15-5278-6_2.

Herzog, T., Krippner, R. and Lang, W. 2012. Facade Construction Manual. Walter de Gruyter.

Hossain, Md. Aslam, Zhumabekova, A., Paul, S.C. and Kim, J.R. 2020. A review of 3D printing in construction and its impact on the labor market. Sustainability 12(20): 8492. https://doi.org/10.3390/su12208492.

Hull, C.W. 1986. Apparatus for production of three-dimensional objects by stereolithography. United States US4575330A, filed August 8, 1984, and issued March 11, 1986. https://patents.google.com/patent/US4575330A/en.

ISO, EN. 2007. 13786: 2007—Thermal Performance of Building Components—Dynamic Thermal Characteristics—Calculation Methods. CEN. European Committee for Standardization 27.

Khoshnevis, B. 2004. Automated construction by contour crafting—related robotics and information technologies. Automation in Construction, The best of ISARC 2002, 13(1): 5–19. https://doi.org/10.1016/j.autcon.2003.08.012.

Kodama, H. 1981. Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. Rev. Sci. Instrum. 52(11): 1770–1773. https://doi.org/10.1063/1.1136492.

Li, Z., Xing, W., Sun, J. and Feng, X. 2023. Multiscale structural characteristics and heat–moisture properties of 3D printed building walls: A review. Constr. Build. Mater. 365: 130102. https://doi.org/10.1016/j.conbuildmat.2022.130102.

Ma, G., Ruhan A, Xie, P., Pan, Z., Wang, L. and Hower, J.C. 2022. 3D-printable aerogel-incorporated concrete: Anisotropy influence on physical, mechanical, and thermal insulation properties. Constr. Build. Mater. 323: 126551. https://doi.org/10.1016/j.conbuildmat.2022.126551.

Maierhofer, D., Röck, M., Saade, M.R.M., Hoxha, E. and Passer, A. 2022. Critical life cycle assessment of the innovative passive nZEB building concept 'be 2226' in view of net-zero carbon targets. Build. Environ. 223: 109476. https://doi.org/10.1016/j.buildenv.2022.109476.

Olgyay, V. 2015. Design with Climate: Bioclimatic Approach to Architectural Regionalism, New and expanded edition. Princeton: Princeton University Press. https://doi.org/10.1515/9781400873685.

Pessoa, S., Guimarães, A.S., Lucas, S.S. and Simões, N. 2021. 3D printing in the construction industry - A systematic review of the thermal performance in buildings. Renewable Sustainable Energy Rev. 141: 110794. https://doi.org/10.1016/j.rser.2021.110794.

Radeloff, V.C., Helmers, D.P., Kramer, H.A., Mockrin, M.H., Alexandre, P.M., Bar-Massada, Avi., et al. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. PNAS. 115(13): 3314–3319. https://doi.org/10.1073/pnas.1718850115.

Reynders, G., Nuytten, T. and Saelens, D. 2013. Potential of structural thermal mass for demand-side management in dwellings. Build. Environ. 64: 187–199. https://doi.org/10.1016/j.buildenv.2013.03.010.

Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., et al. 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl. Energy. 258: 114107. https://doi.org/10.1016/j.apenergy.2019.114107.

Roux, C., Kuzmenko, K., Roussel, N., Mesnil, R. and Feraille, A. 2022. Life cycle assessment of a concrete 3D printing process. Int. J. Life Cycle Assess. 28: 1–15. https://doi.org/10.1007/s11367-022-02111-3.

Sarakinioti, M.-V., Konstantinou, T., Turrin, M., Tenpierik, M., Loonen, R., De Klijn-Chevalerias, M.L., et al. 2018. Development and prototyping of an integrated 3D-printed façade for thermal regulation in complex geometries. J. Facade Des. Eng. 6(2): 029–040. https://doi.org/10.7480/JFDE.2018.2.2081.

Schniederjans, D.G. 2017. Adoption of 3D-printing technologies in manufacturing: A survey analysis. Int. J. Prod. Econ. 183: 287–298. https://doi.org/10.1016/j.ijpe.2016.11.008.

Tinoco, M.P., de Mendonça, É.M., Fernandez, L.I.C., Caldas, L.R., Reales, O.A.M. and Filho, R.D.T. 2022. Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: A systematic literature review. J. Build. Eng. 52: 104456. https://doi.org/10.1016/j.jobe.2022.104456.

Zhang, C., Kazanci, O.B., Levinson, R., Heiselberg, P., Olesen, B.W., Chiesa, G., et al. 2021. Resilient cooling strategies – A critical review and qualitative assessment. Energy Build. 251: 111312. https://doi.org/10.1016/j.enbuild.2021.111312.