Thermal Walls

Enhancing Thermal Properties of Prefabricated Wall Systems with Additive Manufacturing

by
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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Additive manufacturing (or 3D printing) is used to design the properties of any material with high precision. In relation to the construction field, solid clay bricks are structurally sturdy, but they are not designed to be thermally effective since their thermal properties are weakened by their homogeneity. 3D printing tools precisely manipulate the geometry of a brick to design, its thermal conductivity properties without changing the material itself. This thesis investigates the methods to design the thermal properties of a brick via 3D printing. This research employs full scale material models and simulation software to assess the thermal effectiveness of the proposed geometry. The key impact of this research is to contribute towards the development of efficient additively manufactured designs that can be integrated into construction systems in order to overcome the material inefficiency and labor-intensive aspects associated with traditional construction methods.

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Table of Contents

Author’s Declaration ii
Abstract iv
Acknowledgments vi
List of Figures xiv

Chapter 1 | Introduction 1

1.1 Aim and Relevance 2
1.2 Context 4
1.2.1 Brick 4
1.2.1.1 Brick Construction History 4
1.2.1.2 Heat Transfer Energy and Flow 9
1.2.1.3 Heat Transfer Methods Within a Brick 10
1.2.1.4 Construction Bricks Development 12
1.2.2 Additve Manufacturing 15
1.2.2.1 Additve Manufacturing, Modular design, and Construction 15
1.2.2.2 Additve Manufacturing Applications in Construction 17
1.2.3 Passive Building Design 22
1.3 State of the Art 26

Chapter 2 | Methods 35

2.1 Overview 36
2.2 Fabrication Process 38
2.3 Translating Digital to Physical 39
2.4 Clay Body Composition and its Working Properties 40
2.5 Thermal Assessing Methodology 42
2.5.1 Digital Simulations Overview 42
2.5.2 Case Studies and Physical Experimentations 45

Chapter 3 | Research Development 49

3.1 Comparison of Traditional Solid Brick to Hollow Brick 50
3.2 Preliminary Studies of Designed Hollow Bricks 56
3.3 Brick Design Development 60
3.4 Wall Design Development 66
3.5 Physical Experiment Testing of the Proposed Wall 74
3.6 Shadow and Optimized Rain Screen Development 78

Chapter 4 | Discussion 85

4.1 Discussion 86

Chapter 5 | Conclusion and Outlook 93

5.1 Conclusion 94

5.2 Outlook 95

5.2.1 Enhancing Thermal Properties Through Modifying Material Properties 95

5.2.2 Enhancing Thermal Properties Through Filling the Bricks' Cavities with Insulation 98

5.2.3 Enhancing Thermal Properties Through Overhangs and Texture 98

Bibliography 102

List of Figures

Figure 1.1.1 Solid clay bricks in the construction field.
How High Can a Single Brick Wall be Built?. June 11, 2020. https://www.turnbullmasonry.com/how-high-can-a-single-brick-wall-be-built/.

Figure 1.1.2 3D printed clay bricks of the proposed geometry showing thermal gradient across the brick section (Figure 3.3.1 explains
Image by author.

Figure 1.2.1.1.1 Mud-dried bricks.
Mud Brick, https://www.yourhome.gov.au/materials/mud-brick.

Figure 1.2.1.1.2 The development of wall systems throughout the history of construction.
Evolution of Building Elements. 2009. https://fet.uwe.ac.uk/conweb/house_ages/elements/section2.htm.

Figure 1.2.1.1.3 The development of air cavities in wall systems.
Evolution of Building Elements. 2009. https://fet.uwe.ac.uk/conweb/house_ages/elements/section2.htm.

Figure 1.2.1.1.4 The development of thermal insulation as a layer within wall systems.
Martins, A., G. Vasconcelos, and A. Campos Costa. Brick masonry veneer walls: An overview. 2017. Journal of Building Engineering 9, 30, fig. 2. https://www.sciencedirect.com/science/article/abs/pii/S2352710216302881.

Figure 1.2.1.1.5 Face seal wall and rain screen wall.
Face Seal System VS Rainscreen System. February 10, 2020. https://renoguide.ca/face-seal-system-vs-rainscreen-system/.

Figure 1.2.1.2.1 Building enclosure layers.
The Perfect Wall; Applying Science to the Building Enclosure. March 7, 2017. https://deltaacademy.dorken.com/building-enclosure-design-guide/.

Figure 1.2.1.3.1 Heat transfer methods within a brick: conduction, convection, and radiation.
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Figure 1.2.1.3.2 Different brick modules developed in the construction field.
Diagrams developed by author.

Figure 1.2.1.4.1 Digital simulations conduced by THERM software to calculate the u-value of solid bricks and perforated bricks.
Image by author.

Figure 1.2.1.4.2 Engineering brick with 3 cavities
Why do bricks have holes. March 24, 2021 https://thegraduateengineer.com/why-do-bricks-have-holes-in/.

Figure 1.2.2.2.1 3D printed concrete column by ETH Zurich.
ETH Zurich Develops 3D-Printed Concrete Columns. July 23, 2019. https://www.archdaily.com/921635/eth-zurich-develops-3d-printed-concrete-columns.

Figure 1.2.2.2.2 3D printed concrete bridge by ETH Zurich.
First 3D printed and unreinforced concrete bridge. July, 2021. https://ethz.ch/en/news-and-events/eth-news/news/2021/07/3d-printed-and-unreinforced.html.

Figure 1.2.2.2.3 A 12 meter long stainless steel pedestrian bridge, 3D printed by MX3D.
Joris Laarman's 3D-printed stainless steel bridge finally opens in Amsterdam. July 19, 2021. https://www.dezeen.com/2021/07/19/mx3d-3d-printed-bridge-stainless-steel-amsterdam/.

Figure 1.2.2.2.4 3D printed clay panel by IAAC.
WASP and IAAC create 3D printed wall with embedded staircase. April 10, 2019. https://www.3dnatives.com/en/wasp-and-iaac-create-3d-printed-wall-with-embedded-staircase/.

Figure 1.2.3.1 An example of a wind tower in United Arab Emirates (left). A diagram of a wind tower to illustrate the movement of air to achieve natural ventilation or Stack effect (right).

Old Dubai with classical wind tower. https://www.123rf.com/photo_39325247_old-dubai-with-classical-wind-tower.html.
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Figure 1.2.3.2 Flying roof design, Teacher's housing project, by Francis Kere (left). Sketches by Francis Kere (right) to illustrate natural ventilation in Teacher's housing (top right) and school extension (bottom right).

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Figure 1.3.1 Different version of Proton German bricks.
How High Can a Single Brick Wall be Built?, June 11, 2020. https://www.turnbullmasonry.com/how-high-can-a-single-brick-wall-be-built/.

Figure 1.3.2 Digital simulations conduced by THERM software.
Image by author.

Figure 1.3.3 A 3D printed curtian wall with cavities to enhance thermal properties of the wall.
Nemova, Darya, Evgeny Kotov, Darya Andreeva, Svyatoslav Khorobrov, Vyacheslav Olshevskiy, Irina Vasileva, Daria Zaborova, and Tatiana Musorina. Experimental Study on the Thermal Performance of 3D-Printed Enclosing Structures. 2022. Energies 15, 3, fig. 1. file:///C:/Users/esraa/Downloads/energies-15-04230-v2%20(2).pdf.

Figure 1.3.4 A design of 3D printed wall with low infill and high infill.
Puppos, Andrew. Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing. 2021. PhD diss., The University of Arizona, 28., fig.17. https://repository.arizona.edu/bitstream/handle/10150/663222/azu_etd_19381_sip1_m.pdf?sequence=1.

Figure 1.3.5 A 3D printed house in which cavities are designed to enhance thermal properties, TECLA, by by WASP.
Tecla. https://www.3dwasp.com/en/3d-printed-house-tecla/.

Figure 1.3.6 Nexus void is a 3D printed wall prototypes with cavities to enhance thermal properties.
3D printed wall insulated with sponges. April 5, 2021. https://kglakademi.dk/nyheder/arkitektstuderende-vinder-konkurrence-3d-printet-vaeg-isoleret-med-svampe.

Figure 2.2.1 The polycarbonate tube of the Potterbot XLS-1 is attached to the stepper motor.
Image by author.

Figure 2.2.2 A loaded polycarbonate tube is attached to the 3D printer.
Image by author.

Figure 2.3.1 Workflow from digital geometry produced in Rhino (top left), to tool path generated via Simplify 3D, slicer software (top right), to physical print (bottom left).

Image by author.

Figure 2.5.1.1 A diagram that illustrated the equation of the U-value method.
Diagram by author.

Figure 2.5.2.1 A precedent for an apparatus setup that evaluates the thermal effectivness of a wall design panel.

Puppos, Andrew. Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing. 2021. PhD diss., The University of Arizona, 34 and 35, figures. 23 and 24. https://repository.arizona.edu/bitstream/handle/10150/663222/azu_etd_19381_sip1_m.pdf?sequence=1.

Figure 2.5.2.2 Phyiscal experiment precedent to measure the effect of texture on enhancing thermal properties.
Prasittisopin, Lapyote, Kittisak Pongpaisanseree, Patiphat Jiramarootapong, and Chalermwut Snguanyat. Thermal and Sound Insulation of Large-Scale 3D Extrusion Printing Wall Panel. 2020. In RILEM International Conference on Concrete and Digital Fabrication, 1177, fig. 2.

Figure 3.2.1 The diagrams illustrate the that the loops designed increase th time heat takes to travel from point A to point B (left) in comparison to a traditional brick (right).
Image by author.

Figure 3.2.2 Module 1.
Image by author.

Figure 3.2.3 Module 2.
Image by author.

Figure 3.2.4 Module 3.
Image by author.

Figure 3.2.5 Module 4.
Image by author.

Figure 3.2.6 Module 5.
Image by author.

Figure 3.2.7 Module 6.
Image by author.

Figure 3.3.1 Step 1 | Solid brick.
Image by author.

Figure 3.3.2 Step 2 | Carving out the brick.
Image by author.

Figure 3.3.3 Step 3 | Introduction of the overlapping lips.
Image by author

Figure 3.3.4 Step 4| Introduction of circular thermal loops.
Image by author.

Figure 3.3.5 Step 5 | Design of mortar.
Image by author.

Figure 3.3.6 Step 6 | Introduction of insulation, polyethylene foam, 0.05 W/m2-k.
Image by author.

Figure 3.4.1 The diagram illustrate the development brick system (Top), The images demonstrate the placement of mortar within the developed proposed geometry.
Image by author.

Figure 3.4.2 The proposed geometry are staggered at this stage instead of being stacked to achieve stability of the bricks.
Image by author.

Figure 3.4.3 (a) Bisque fired 3D printed clay bricks are stacked using a rubber sealant.
Image by author.

Figure 3.4.3 (b) Bisque fired 3D printed clay bricks are stacked using a rubber sealant.
Image by author.

Figure 2.5.1 Phyiscal experiment setup.
Image by author.

Figure 2.5.2 Diagram of the physical experiment that shows the placement of the temperature probes.
Image by author.

Figure 2.5.3 The graph illustrates the temperature change of each experiment versus time.
Image by author.

Figure 3.6.1 Rectangular shaped traditional clay bricks.
Image by author.

Figure 3.6.2 3D printed clay bricks of this research has slanted overhangs.
Image by author.

Figure 3.6.3 Wall facing East.
Image by author

Figure 3.6.4 Wall facing West.
Image by author.

Figure 4.1.1 Measuring the u-value of solid clay brick.
Image by author.

Figure 4.1.2 Measuring the u-value of engineering brick with 3 cavities.
Image by author.

Figure 4.1.3 Measuring the u-value of German brick.
Image by author.

Figure 4.1.4 Measuring the u-value of this research's brick design.
Image by author.

Figure 5.2.1 Step 5 | Design of the proposed brick.
Image by author.

Figure 5.2.2 Step 5 | changing the properties of clay through modifying material properties.
Image by author.

Figure 5.3.1 Step 5 | Design of the proposed brick.
Image by author.

Figure 5.3.2 Step 6 | Introduction of insulation, polyethylene foam, 0.05 W/m2-k.
Image by author.

Figure 5.4.1 Enhancing the thermal conductivity through the design of overhangs.
Henke, Klaudius, Daniel Talke, and Carla Matthäus. Additive manufacturing by extrusion of lightweight concrete-strand geometry, nozzle design and layer layout.2020. In RILEM International Conference on Concrete and Digital Fabrication, 913, fig. 7.

Figure 5.4.2 Enhancing thermal properties through the design of texture, Chanita Chuaysiri.
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Chapter 1

Introduction

1.1 Aim and Relevance

This research focuses on enhancing thermal properties of a brick unit without changing the material itself but rather by investigating the effect of geometry, both external shape and internal geometric structure, on the thermal conductivity of the brick. Solid clay bricks in the construction field are structurally sturdy (Figure 1.1.1). However, they are not designed to be thermally effective since their thermal properties are weakened by their homogeneity. This thesis aims to design and test the thermal properties of a brick via 3D printing methods. In particular, 3D printing tools manipulate the geometry of a brick to design its thermal conductivity properties (Figure 1.1.2).

This research focuses on only designing one brick, rather than designing the entire wall. The development of the brick is centered on infill (or the internal structure and shape of the brick unit) that can be modified to improve the thermal performance. The brick prototypes will optimize the infill of a 3D printed brick unit for hot climate conditions. The proposed brick is positioned in hot climate because air is a more effective insulator than solids as solids can transmit heat through conduction[1]. Hot desert climates are typically found under the subtropical ridge in the lower middle latitudes, between 20° and 33° north and south latitudes[2]. Hot desert climates are found across expansive areas of North Africa, Western Asia, and some parts of the Southwestern United States[3].

1. Andrew Puppos, "Printing Clay: Design Optimization for 3D Printing Sustainable," 28.
2. Vic Lang'at Junior, "What is a Desert Climate?," last modified November 1, 2017, https://www.worldatlas.com/articles/what-is-a-desert-climate.html.
3. Vic Lang'at Junior, "What is a Desert Climate?,"

Figure 1.1.1 | Solid clay bricks in the construction field.

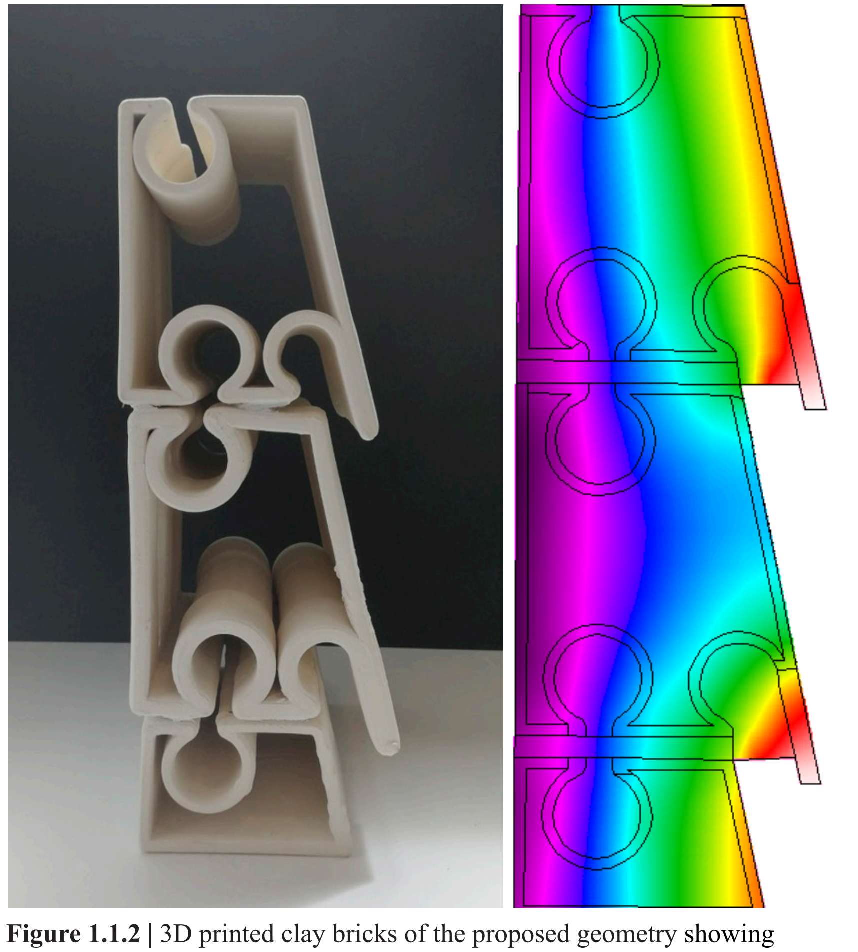


Figure 1.1.2 | 3D printed clay bricks of the proposed geometry showing thermal gradient across the brick section (Figure 3.3.1 explains in detail the thermal gradient).

1.2 Context

This research aims to use additive manufacturing to develop thermally efficient bricks. In this section, the context of this research is discussed. This includes the position of this development in the continuum of brick history, as well as the role of additive manufacturing in related construction applications.

1.2.1 Brick

This subsection delves into the history of brick construction and the development of building enclosures. Moreover, this subsection also discusses the methods of heat transfer energy and its flow within bricks.

1.2.1.1 Brick Construction History

Bricks are one of the oldest known building materials, dating back to 7000 BC.[4] Mud bricks, dried in the sun for hardening, were the first bricks made in warm climates (Figure 1.2.1.1.1). Around 3,500 BC, fired bricks were invented which, unlike air dried- bricks, are not softened by rain.[5] Moreover, fired bricks could also be manufactured without the heat of sun and quickly gained popularity in cooler climates.

Brick masonry is a traditional construction material that has been extensively implemented in the construction of enclosure walls, specifically masonry infills and veneer walls, that separate the interior and exterior environments.

4. "The History of Bricks and Brickmaking," Brick Architecture, accessed October 27, 2022, https://brickarchitecture.com/about-brick/why-brick/the-history-of-bricks-brickmaking.
5. "The History of Bricks and Brickmaking," Brick Architecture.

Figure 1.2.1.1.1| Mud-dried bricks.

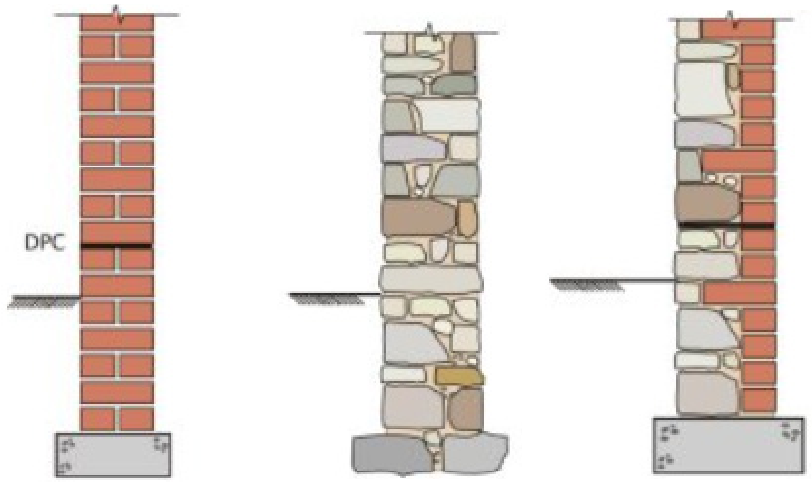


Figure 1.2.1.1.2 | The development of wall systems throughout the history of construction.

Single leaf walls made of stone, brick, or adobe were prominent of the façade walls in European countries up to the middle of the 20th century, providing the overall stability and durability of the structures (Figure 1.2.1.1.2 and 1.2.1.1.3).[6] However, masonry walls lost their structural function and became largely non load bearing walls with the emergence of structural solutions other than structural masonry, such as reinforced concrete frames.[7]

In the past, enclosure walls were constructed as masonry cavity walls, consisting of two leaves separated by an air cavity that was filled with insulating material to improve the thermal performance (Figure 1.2.1.1.4).[8] However, the development of brick veneer walls was prompted by the need to either prevent or minimize thermal bridge issues.[9] The brick veneer walls act as an outer envelope wall in relation to the structural system. A masonry veneer wall refers to an exterior masonry cladding that serves as the structure's skin. The Veneer wall is separated from the structural framework by an air cavity. The structural backing system differs based on the traditional construction technology.[10]

Rainwater penetration is a key source of concern in the performance of building envelopes. For years, low-rise building construction has employed mass walls to avoid rainwater penetration. The main drawback of such walls is the use of vast amounts of material and labor required to build them.

6. A. Martins et al., "Brick masonry veneer walls: An overview," *Journal of Building Engineering 9* (2017): 30, accessed October 4, 2022. https://www.sciencedirect.com/science/article/abs/pii/S235271021630288.
7. A. Martins et al., "Brick masonry veneer walls: An overview," 30.
8. A. Martins et al., "Brick masonry veneer walls: An overview," 30.
9. A. Martins et al., "Brick masonry veneer walls: An overview," 30.
10. A. Martins et al., "Brick masonry veneer walls: An overview," 30.

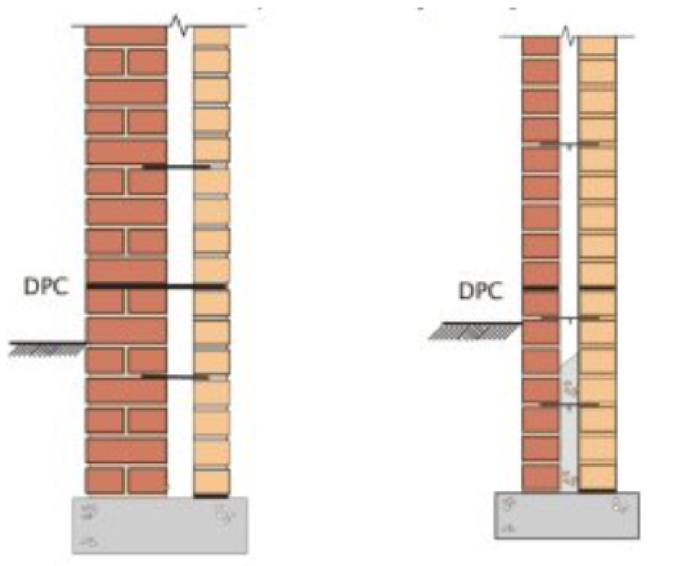


Figure 1.2.1.1.3 | The development of air cavities in wall systems.

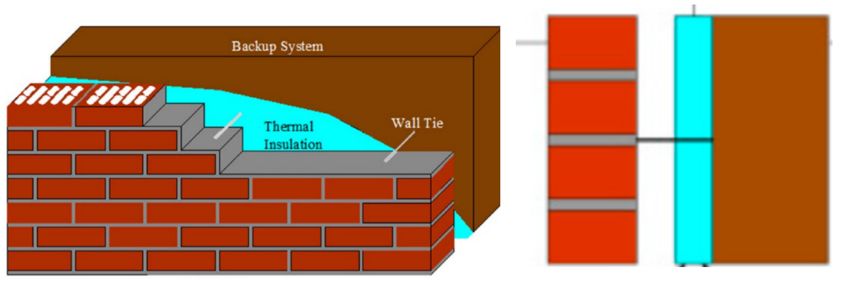
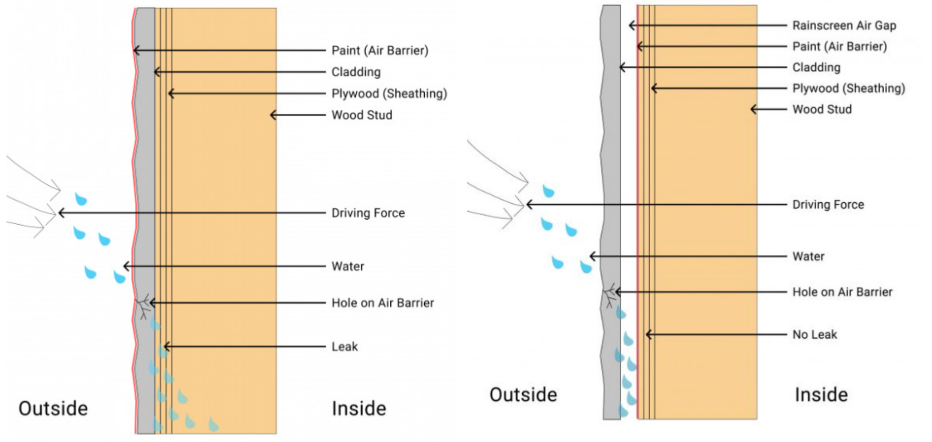


Figure 1.2.1.1.4 | The development of thermal insulation as a layer within wall systems.



Face seal wall **Rain screen Wall**

Figure 1.2.1.1.5 | Face seal wall and rain screen wall.

Face-sealed walls were established after understanding the limitations of mass wall systems to control rainwater penetration through the walls by sealing the joints between the panels.[11] Finally, researchers realized that rainwater penetration cannot be completely controlled; a small amount of rainwater may still seep through any mass- or face-sealed wall. As a result, a screen would help in keeping out most of the rainwater falling on the panel face and a good drainage system to drain any water that did penetrate. These ideas resulted in the development of current screened wall systems (Figure 1.2.1.1.5).[12]

The rainscreen's principal role is to keep the majority of the driving rain away from the structural leaf (air barrier). Using pressure equalization mechanism, the rainwater penetration caused by wind-induced differential pressure is also reduced. Further, it protects the air barrier from solar radiation, pollutants, heat, fire and other environmental factors. The various design features of rainscreen concerning only the rain penetration aspect are "(a) total venting area, (b) venting location, (c) venting dimension, (d) rainscreen design loads, and (e) rainscreen stiffness".[13]

11. K. Suresh Kumar, "Pressure equalization of rainscreen walls: a critical review," *Building and Environment* 35, no. 2 (2000): 161, accessed October 4, 2022. https://www.sciencedirect.com/science/article/abs/pii/S0360132399000153.
12. K. Suresh Kumar, "Pressure equalization of rainscreen walls: a critical review," 163.
13. K. Suresh Kumar, "Pressure equalization of rainscreen walls: a critical review," 163.

1.2.1.2 Heat Transfer Energy and Flow

One of the methods to decrease the energy content of buildings is through the selection of building materials. Strain on energy resources can be reduced by the utilization of low embodied energy building materials and efficient structural design. The choice of materials also helps to maximize the comfort of the indoor environment. The use of materials and components with small, embodied energy or low thermal conductivity can enhance people's indoor comfort in buildings.[14] The utilization of low thermal conductivity building materials is important to decrease heat gain through the envelope into the building especially in hot climate zones.[15] The construction industry decouples the brick cladding function from the insulation function. However, this research aims to join the brick cladding function with the insulation function because it is more efficient in hot climatic zones.

Physical barriers and energy are the main aspects that need to be regulated in order to achieve environmental control.[16] While the fundamentals of building enclosure design involve water or rain control, air flow control, thermal and vapor control, this research thesis focuses only on the thermal aspect of the building enclosure due to the restricted thesis timeline (Figure 1.2.1.2.1). Thermal properties of the building envelope materials have a significant role in determining the thermal behavior of buildings.

14. Md Azree Othuman Mydin , "Effective thermal conductivity of foamcrete of different densities,"*Concr. Res. Lett 2*, no. 1 (2011): 182, accessed October 4, 2022. https://core.ac.uk/download/pdf/234103078.pdf.
15. Md Azree Othuman Mydin, "Effective thermal conductivity of foamcrete of different densi ties,"182.
16. Albert Joseph Elder*, AJ Handbook of Building Enclosure* (London: Architectural Press, 1974), 9.

Understanding the thermal properties is a key aspect in buildings as it is necessary for assessing energy use, thermal comfort, thermal movements, durability, and the potential for moisture problems.

The design of a 3D printing (3DP) thermally informed masonry unit requires an understanding of the heat transfer flow and the distribution of the temperature through building materials. One of the important requirements of a building in hot climates, is its ability to provide thermal comfort without the need for excess air conditioning costs.[17] Thus, understanding how the temperature is distributed through the building materials can bring possibilities to design those materials thermally through their geometries.

1.2.1.3 Heat Transfer Methods Within a Brick

The three methods of transferring heat through a brick are conduction, convection, and radiation (Figure 1.2.1.3.1).[18] Conduction occurs through the solid part of the bricks, while the heat transfer by convection and radiation occurs between the ambient air and the outer and inner wall surfaces, as well as through air cavities of the hollow bricks. The geometry of a brick has evolved over the course of the construction history. Traditionally, clay bricks were built in a solid shape without any cavities.[19] (Figure 1.2.1.3.2-A).

17. John Straube, "Thermal Control in Buildings," last modified December 12, 2011, https://www.buildingscience.com/documents/digests/bsd-011-thermal-control-in-buildings.
18. Ahmed S. Al-Tamimi et al., "Effect of geometry of holes on heat transfer of concrete ma sonry bricks using numerical analysis," *Arabian Journal for Science and Engineering* 42, no. 9 (2017): 3734, accessed October 4, 2022. https://link.springer.com/article/10.1007/s13369-017-2482-6.
19. Ahmed S. Al-Tamimi et al., "Effect of geometry of holes," 3734.

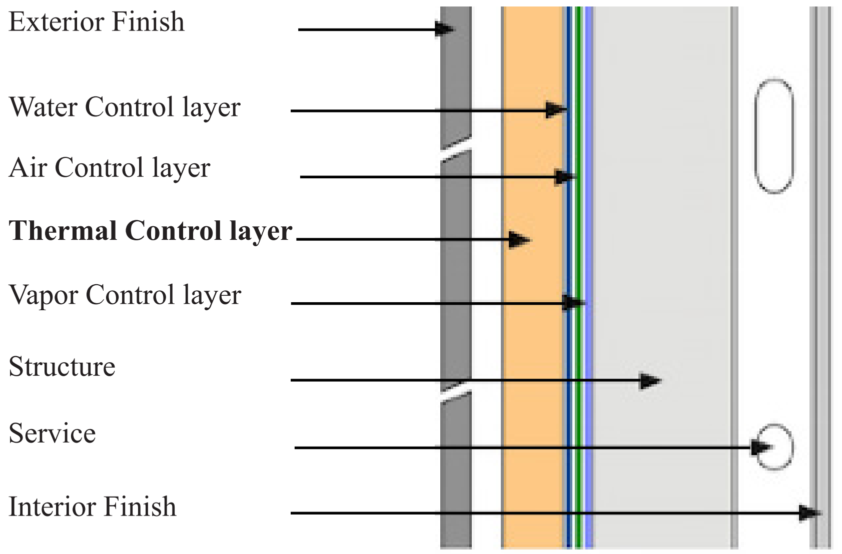


Figure 1.2.1.2.1 | Building enclosure layers.

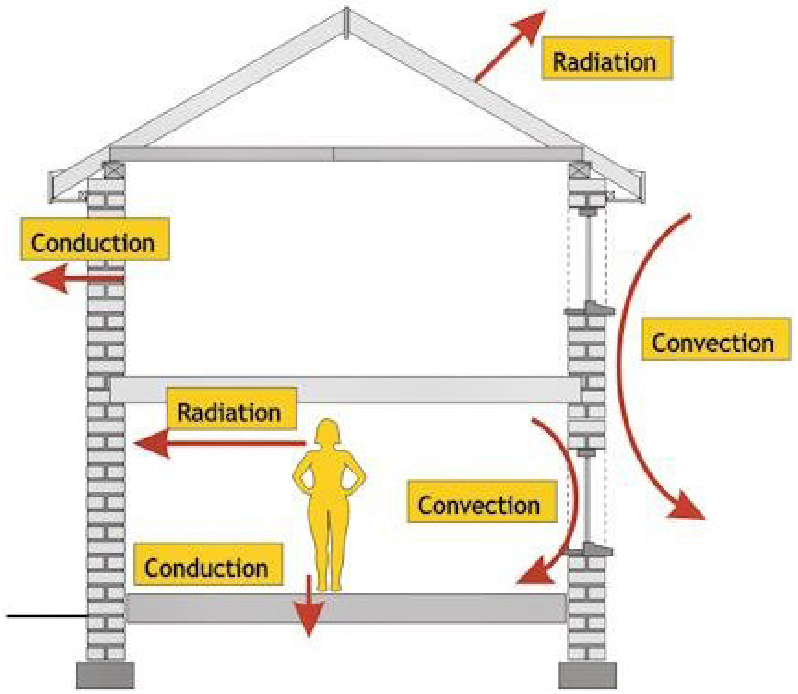


Figure 1.2.1.3.1 | Heat transfer methods within a brick: conduction, convection, and radiation.

However, the introduction of cavities in the design of a brick had a direct impact on the heat transfer (Figure 1.2.1.3.2-B).[20] In particular, increasing the number of cavities tended to decrease the heat transfer from outer to inner brick sides significantly through trapping air inside the cavities, in comparison to the solid models.[21]

1.2.1.4 Construction Bricks Development

While increasing the void to solid ratio tends to decrease the heat transfer, cavities can make the individual brick structurally weaker. When designing a brick, the ratio between the number of cavities in the brick and its size is important to consider. Moreover, the shape of the cavity also influences structure of the brick. For instance, round cavities are more structurally stable than rectangular holes because the stress in a round shape is distributed equally along the arc instead of concentrating at any one point (Figure 1.2.1.3.2 C and D).[22] Therefore, the round shape is stronger than the square shape where cracks happen at the edges of the square.[23]

This research defines a baseline point on how conventional bricks compare in terms of thermal conductivity by conducting digital simulation using THERM. THERM software is a heat analysis tool described in detail in Section 2.5.1. The u-value of Bricks A and B were measured using THERM (Figure 1.2.1.4.1).

20. Ahmed S. Al-Tamimi et al., "Effect of geometry of holes," 3734.
21. Ahmed S. Al-Tamimi et al., "Effect of geometry of holes," 3734.
22. Ahmed S. Al-Tamimi et al., "Effect of geometry of holes," 3742.
23. Ahmed S. Al-Tamimi et al., "Effect of geometry of holes," 3742.

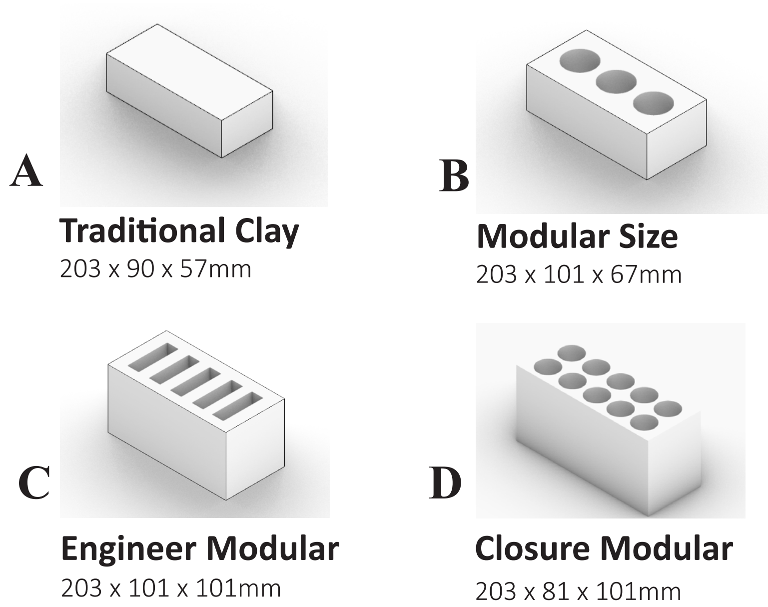


Figure 1.2.1.3.2 | Different brick modules developed in the construction field.

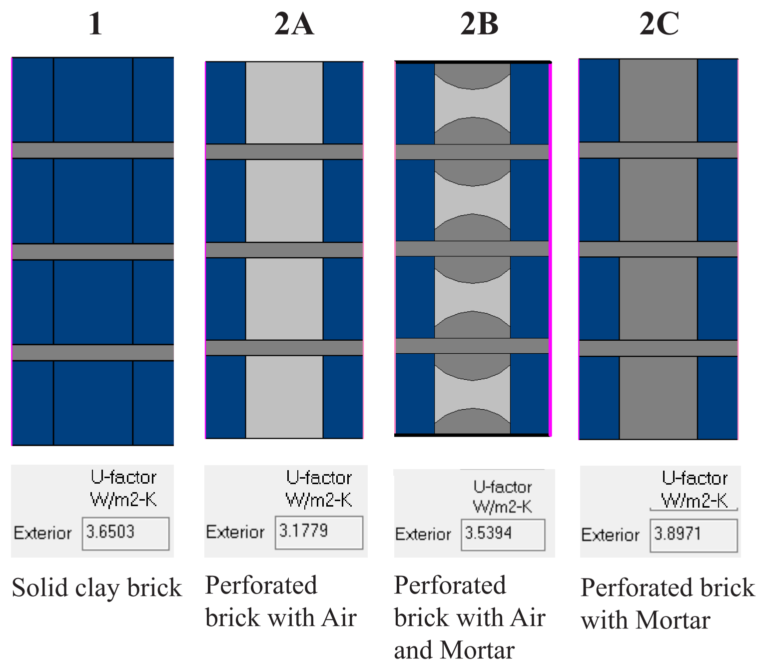


Figure 1.2.1.4.1 | Digital simulations conduced by THERM software to calculate the u-value of solid bricks and perforated bricks.

Figure 1.2.1.4.2 | Engineering brick with 3 cavities.

These u-values will be compared to the 3D printed brick developed in this research and the results will be investigated in the discussion chapter. According to the simulations from THERM software, the solid clay brick has a u-value of 2.65 W/m2-k. Brick B is an engineering brick with 3 cavities and these cavities are filled with mortar during stacking, hence the u-value is measured without and with the mortar (Figure 1.2.1.4.2). The u-value of Ubrick+air is 3.18 W/m2-k, Ubrick+air+mortar is 3.54 W/m2-k and Ubrick+mortar is 3.90 W/m2-k.

1.2.2 Additive Manufacturing

This subsection discusses additive manufacturing in relation to modular design, and building construction applications.

1.2.2.1 Additive Manufacturing, Modular design and Construction

Modular design involves assembling multiple pre-fabricated modules to create a working unit. Modern construction systems frequently incorporate modular designs due to their design flexibility and lower construction time.[24] Additive manufacturing (AM), as an important tool in developing modular design, is expected to transform the brick manufacturing industry.[25] AM is distinguished by a rapid and "low-cost building process".[26] The integration of a modular building system with additive manufacturing processes can replace the traditional manufacturing processes and can provide a sustainable solution to the modern construction challenges.[27]

AM is one of the modern manufacturing techniques arising in the construction industry.[28] AM is the process of creating components by depositing and fusing materials layer by layer. Materials are bonded to each other by either fusion, binding or

24. Lilly Cao, "Why Choose Modular Construction?," last modified October 16, 2020, https://www.archdaily.com/949219/ why-choose-modular-construction.
25. Ingrid Paoletti. "Mass customization with additive manufacturing: new perspectives," *Procedia engineering* 180 (2017): 1159.
26. Darya Nemova et al., "Experimental Study on the Thermal Performance," last modified June 8, 2022, https://www.mdpi.com/1996-1073/15/12/4230.
27. Darya Nemova et al., "Experimental Study on the Thermal Performance of ".
28. Alexander Paolini et al., Additive manufacturing in construction: A review on processes,"

sintering - among many others. AM creates parts layer by layer based on geometric information from 3D CAD models. AM processes develop components using 3D computer data or Standard Tessellation Language (STL) files, which includes the information on the geometry of the object. AM is useful when high design complexity, and frequent design changes are required.[29] It enables the production of complex parts by overcoming the design limits of traditional manufacturing methods such as casting or molding.[30]

AM is useful for product design optimization, as recent research indicates that the free-form fabrication nature of AM removes some of the design constraints of traditional manufacturing processes and enables the redesign or the optimization of the products, like the need for expensive molds for prototypes.[31] The lower cost associated with prototype development and tests for new design iterations make it more cost effective to redesign or optimize products. Therefore, the optimal design will allow the reduction of the materials, energy, fuel or natural resources in the product manufacturing and operation process and the enhancement of the product performance, bringing significant economic benefits and improving sustainability.

29. Osama Abdulhameed et al., "Additive manufacturing: Challenges, trends, and applications."
30. Osama Abdulhameed et al., "Additive manufacturing: Challenges, trends, and applications."
31. Liang Hao el al., "Enhancing the sustainability of additive manufacturing," 390.

AM might also be a suitable technology to replace processes where significant amounts of energy are wasted changing the phase of materials from solid to liquid, such as casting or molding.[32] Thus, many resources spent on the fabrication of specific tooling for the production can be saved.

1.2.2.2 Additive Manufacturing Applications in Construction

AM is envisioned to revolutionize the manufacturing industry of clay and concrete and might offer a different approach to construction. This is due to their potential to modify traditional building practices and automatically produce building elements with complex geometries. This construction technique can potentially make more efficient use of materials and reduce construction costs. It can also reduce manpower which decreases injuries and fatalities on construction sites and increases sustainability of the construction industry.[33] Although prototypes and visual models have been produced using additive manufacturing for years, the direct manufacturing method generating an end-ready-to-use product is a recent development in AM technology.[34]

32. Liang Hao et al., "Enhancing the sustainability of additive manufacturing." 390.
33. Meron Mengesha et al., "Numerical Modeling of an Extrusion-Based 3D Concrete Printing Process Considering a Spatially Varying Pseudo-Density Approach,".
34. Ingrid Paoletti, "Mass customization with additive manufacturing: new perspectives for multi performative building components in architecture," 1150.

Despite the advantages of design flexibility and material optimization, the implementation of 3D printing in the construction industry has been slow and limited.[35] Nonetheless, additive manufacturing remains a promising research field in architecture as it can be leveraged to design the properties of a material with high precision. In additive manufacturing for construction, there have been three major material directions: concrete, steel, and clay.[36]

The majority of additive manufacturing investigations has been on 3D printed concrete. This includes bridges and column applications developed by ETH Zurich's research group.[37] The group designed 3D printed concrete columns (Figure 1.2.2.2.1) that do not require formwork, resulting in a more sustainable approach to concrete building. The columns are built as hollow constructions to allow for the strategic use of materials. This process is predicted to significantly enhance concrete construction efficiency while allowing for the manufacture of complex components.[38] This is due to the adaptability and significant aesthetic potential 3D concrete printing possesses when applied in large scale constructions. The computationally generated material decoration and surface texture that are used in their work serve as evidence of this.

35. Tuan D. Ngo et al., "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," 172.
36. Jubert Pasco et al.,"Additive Manufacturing in Off-Site Construction: Review and Future Directions," 53.
37. Niall Patrick Walsh, "ETH Zurich Develops 3D-Printed Concrete Columns," last modified July 21, 2019. https://www.archdaily.com/921635/eth-zurich-develops-3d-printed-con crete-columns.
38. Niall Patrick Walsh, "ETH Zurich Develops 3D-Printed Concrete Columns,"

Another work by ETH's research group that focused on 3D printing concrete is a bridge design (Figure 1.2.2.2.2). The bridge's design incorporate an optimized load-bearing arch structure composed of modular components. The geometry and fabrication strategy allows the design to be built with significantly less concrete and no mortar or steel reinforcement.[39] The strategic use of geometry and meso-structure design of each component also contributes to the bridge's strength. Since it is a masonry bridge, it is convenient to deconstruct the bridge and reconstruct it in other locations. Furthermore, the ability to separate and recycle the 3D printed bridge when the construction is no longer needed, makes the design process more sustainable.[40]

Metal 3D printing has also been of interest for bridges such as Joris Laarman's 3D-printed stainless-steel bridge in Amsterdam (Figure 1.2.2.2.3). A 12-meter-long stainless-steel pedestrian bridge was 3D printed by MX3D. According to Michael Walther, the pedestrian bridge is well-suited to the needs of the construction industry of size, speed, and affordability.[41] The key feature of this project is the use of wire and arc additive manufacturing (WAAM) technology. This means that the 3D printer is composed of a gas metal arc welding machine and a 6-axis industrial robot capable of producing metal rods that are self-supportingly. Thus, large metal constructions may be produced in this manner.[42]

39. Michael Walther, "First 3D printed and unreinforced concrete bridge," Last modified July 19, 2021. https://ethz.ch/en/news-and-events/eth-news/news/2021/07/3d-printed-and-unrein forced.html.
40. Michael Walther, "First 3D printed and unreinforced concrete bridge,".
41. Leroy Gardner, "Testing and initial verification of the world's first metal 3D printed bridge,"
42. Alexander Paolini et al., "Additive manufacturing in construction: A review on processes,".

Clay 3D printing has also been investigated for the fabrication of various applications such as wall panels and 3D printed houses (Figure 1.2.2.2.4). IAAC has created 3D printing solutions for load-bearing Earthen Structures.[43] In particular, this project makes use of modularity by combining, manipulating, twisting, and deforming modules to generate spatial solutions in the form of series of rooms and single architectural features such as staircases, apertures, and columns.[44]

43. IAAC, "IAAC and WASP: New 3D Printing Strategies Towards the Realisation of Load-bearing Earthen Structures," Last modified July 21, 2019. https://iaac.net/iaac-wasp-new-3d-printing-strategies-towards-realisation-load-bearing-earthen-structures/.
44. IAAC, "IAAC and WASP: New 3D Printing Strategies Towards the Realisation of Load-bearing Earthen Structures,"

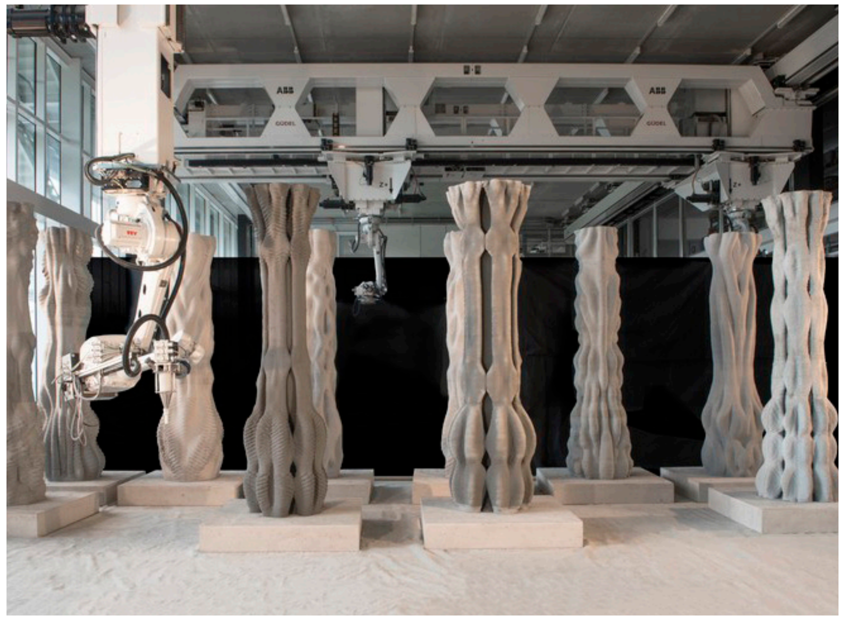


Figure 1.2.2.2.1 | 3D printed concrete column by ETH Zurich.

Figure 1.2.2.2.2 | 3D printed concrete bridge by ETH Zurich.

1.2.3 Passive Building Design

Passive building design aims to achieve high energy efficiency while also providing comfortable indoor living spaces.[45] In particular, design principles such as air trapping and air movement (i.e. moving warm air out of the building) can be employed to achieve cooling effect within a building while reducing energy consumption.

The trapped air, within the building brick cavities, acts as a poor conductor of heat, and therefore, air acts as a barrier to heat transfer. Therefore, the insulating effect of the trapped air (as discussed in Sections 1.2.1.4 and 1.2.1.5) regulates the indoor temperature. Moreover, as will be discussed in Section 1.3, additive manufacturing can shape the air cavities inside the brick and hence, improves the thermal insulation properties of a brick.

The concept of providing comfortable indoor living is not limited to trapping air, but also depends on the movement of air. Therefore, an understanding of how trapped air is displaced out of a building is an important aspect of dry, arid and hot climatic zones.

Passive ventilation and cooling are important for buildings in hot and arid climates.[46] For instance, in areas with limited access to electricity, a cooling indoor effect can be created by displacing out the trapped warm air out of the buliding.[47]

45. “Passive Building Principles,”phius, accessed October 27, 2022, https://www.phius.org/passive-building/what-passive-building/passive-building-principles.
46. Chohan, et al. “Wind Catchers: An Element of Passive Ventilation in Hot, Arid and Humid Regions, a Comparative Analysis of Their Design and Function,” 11088.
47. Chohan, et al. “Wind Catchers: An Element of Passive Ventilation in Hot, Arid and Humid Rions, a Comparative Analysis of Their Design and Function,” 11088.

Figure 1.2.2.2.3 | A 12 meter long stainless steel pedestrian bridge, 3D printed by MX3D.

Figure 1.2.2.2.4 | 3D printed clay panel by IAAC.

This passive movement of air through a building, resulting from the differences in vertical pressure, is referred to as stack effect.[24] For example, wind catchers are traditionally adopted for ventilation in areas such as the United Arab Emirates, Iraq and Egypt (Figure 1.2.3.1).[48] A wind catcher (or a wind tower) is "an elevated chimney-like structure" installed on a building's roof that allows warm air to escape using the stack effect.[49]

In recent work, Francis Kere combined vernacular passive cooling strategies with modern technology in many of his projects in Africa to provide relief from hot outdoor temperatures.[50] According to Kere, the design of *flying roof* provides a solution by dividing the roof and ceiling into two separate components.[51] By integrating cavities into the ceiling, the flying roof design allows warm air to escape (Figure 1.2.3.2).[52] Moreover, a metal roof, placed above the ceiling, shields against sun, and facilitates air circulation between the ceiling and the roof. [53] Consequently, this flying roof design reduces the indoor temperature and creates passive cool ventilation effect.[54] Thus, natural heat convection and stack ventilation can provide comfort without the use of energy sources.[55]

48. Chohan, et al. "Wind Catchers: An Element of Passive Ventilation in Hot," 11088.
49. Chohan, et al. "Wind Catchers: An Element of Passive Ventilation in Hot," 11088.
50. "Natural Ventilation," kerefoundation, accessed October 4, 2022, https://www.kerefoundation.com/en/practices/architecture.
51. "Natural Ventilation," kerefoundation.
52. "Natural Ventilation," kerefoundation.
53. "Natural Ventilation," kerefoundation.
54. "Natural Ventilation," kerefoundation.
55. "Stack Ventilation: A Comprehensive Overview," Linquip Team.

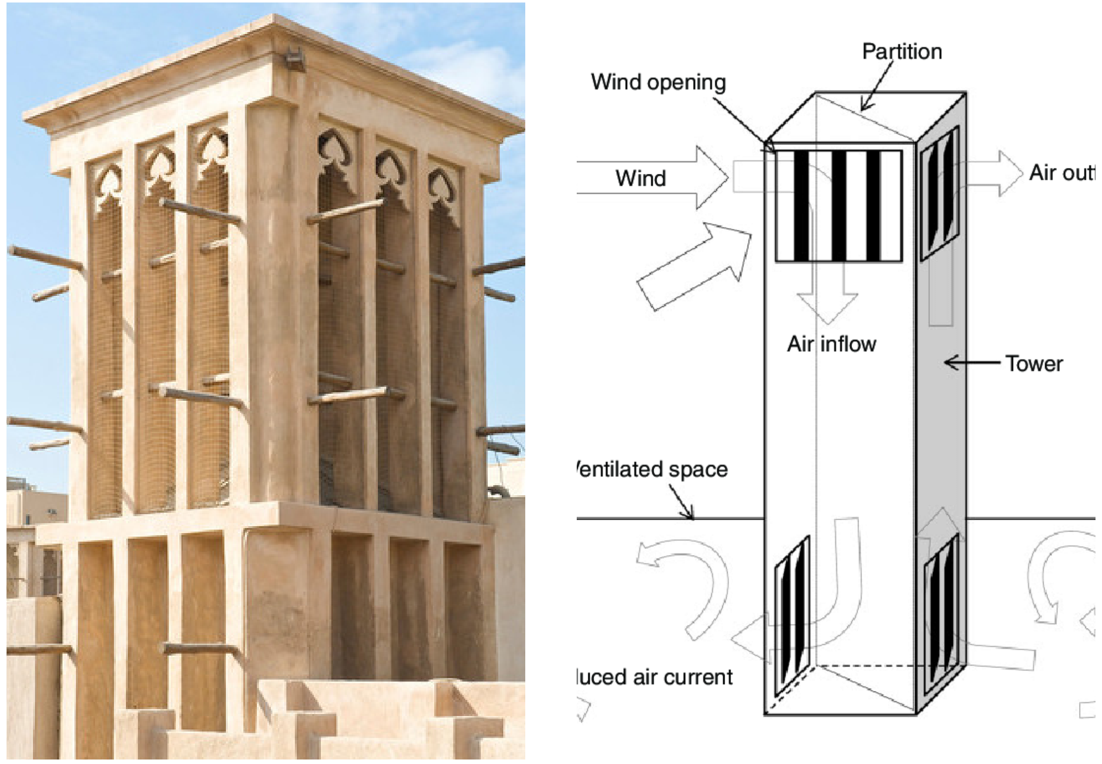


Figure 1.2.3.1 | An example of a wind tower in United Arab Emirates (left).
A diagram of a wind tower to illustrate the movement of air to achieve natural ventilation or Stack effect (right).

Figure 1.2.3.2 | Flying roof design, Teacher's housing project, by Francis Kere (left).
Sketches by Francis Kere (right) to illustrate natural ventilation in Teacher's housing (top right) and school extension (bottom right).

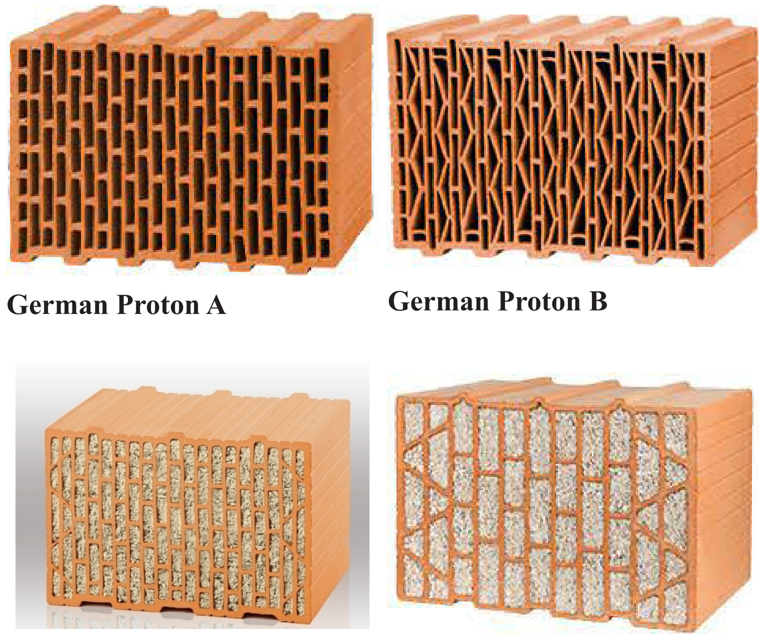
1.3 State of the Art

Additive manufacturing produces methods to improve the thermal properties of a wall. In particular, 3D printing tools shape the geometry of a brick to design the thermal conductivity properties of a 3D printed brick unit. The brick design includes the external shape of the brick but also the infill (or the internal structure).

Efforts have been made by the construction industry to improve the thermal insulation levels of the clay blocks. Proton Bricks, Optimized Clay bricks with Perlite insulation, were developed in Germany (Figure 1.3.1).[56] The product developers at Schlagmann Poroton designed a module that can fill the insulation into the clay block instead of adhering it to the outside of the block.[57] With the patented perlite filling, the clay block have enhanced thermal properties while preserving its structural properties.[58]

THERM software was used to calculate Brick's C u-value (Figure 1.3.2). These u-values will be compared to the 3D printed brick developed in this research and the results will be compared and analyzed in context within the discussion chapter. According to the simulations from THERM software, the German proton brick has a u-value of 2.41 W/m2-k when filled with air only, and u-value of 1.66 W/m2-k when filled with polyethylene foam.

56. "20 years of perlite clay blocks," Ziegelindustrie International, accessed October 20, 2022, https://www.zi-online.info/en/artikel/zi_20_years_of_perlite_clay_blocks_3686600.html.
57. "20 years of perlite clay blocks," Ziegelindustrie International.
58. "20 years of perlite clay blocks," Ziegelindustrie International.



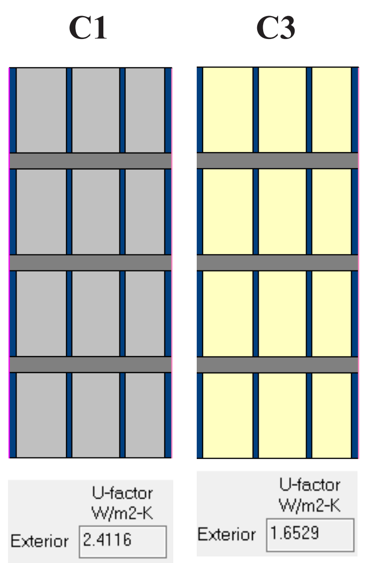
German Proton A

German Proton B

German Proton C

German Proton D

Figure 1.3.1 | Different version of Proton German bricks. The cavities of German Proton 1 and 2 are filled with air (top). The cavities of bricks 3 and 4 are filled with Perlite insulation (bottom).



German Proton brick with Air

German Proton brick with polyethylene foam

Figure 1.3.2 | Digital simulations conduced by THERM software to calculate the u-value of Proton German brick with air and with polyethylene foam insulation.

There has been limited work on 3D printing research that includes thermal performances when printing a building. Some project initiatives and research studies have looked into the possibility of employing 3D printing to create building components with improved thermal characteristics.[59] A study has been conducted to measure the thermal performance of 3D-printed enclosures.[60]

The study showed that the cavities inside the 3DPC curtain walls have a significant impact on the thermal conductivity of the wall. The insulating properties can be enhanced by including cavities in areas that need low heat conductivity and the wall's thermal properties can be further enhanced using stone wool insulation to fill the curtain wall's cavities (Figure 1.3.3). According to the study's findings, the heat flux—"or the quantity of heat energy passing through the solid components of 3D-printed structures"—is significantly larger (by up to two) than the heat flux via the structures' air parts.[61]

Another study attempted to decrease the heat conductivity route in 3D printed wall components.[62] Two wall panels, with identical external geometry and different inner print cross-sections, were built for comparison.

59. Darya Nemova et al., "Experimental Study on the Thermal Performance of 3D-Printed Enclosing Structures."
60. Darya Nemova et al., "Experimental Study on the Thermal Performance of 3D-Printed Enclosing Structures."
61. Darya Nemova et al., "Experimental Study on the Thermal Performance of 3D-Printed Enclosing Structures."
62. Darya Nemova et al., "Experimental Study on the Thermal Performance of 3D-Printed Enclosing Structures."

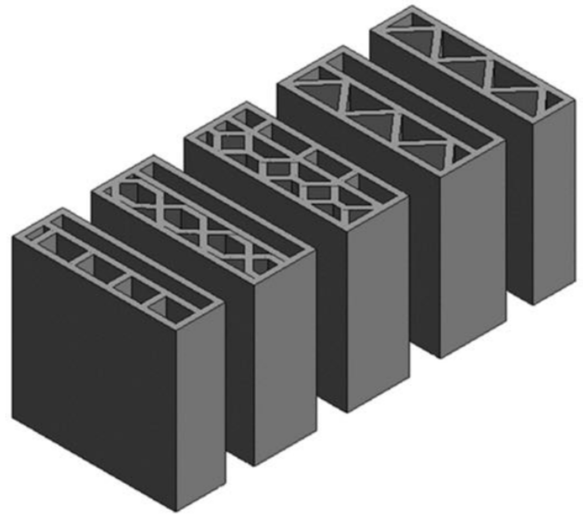


Figure 1.3.3 | A 3D printed curtian wall with cavities to enhance thermal properties of the wall.

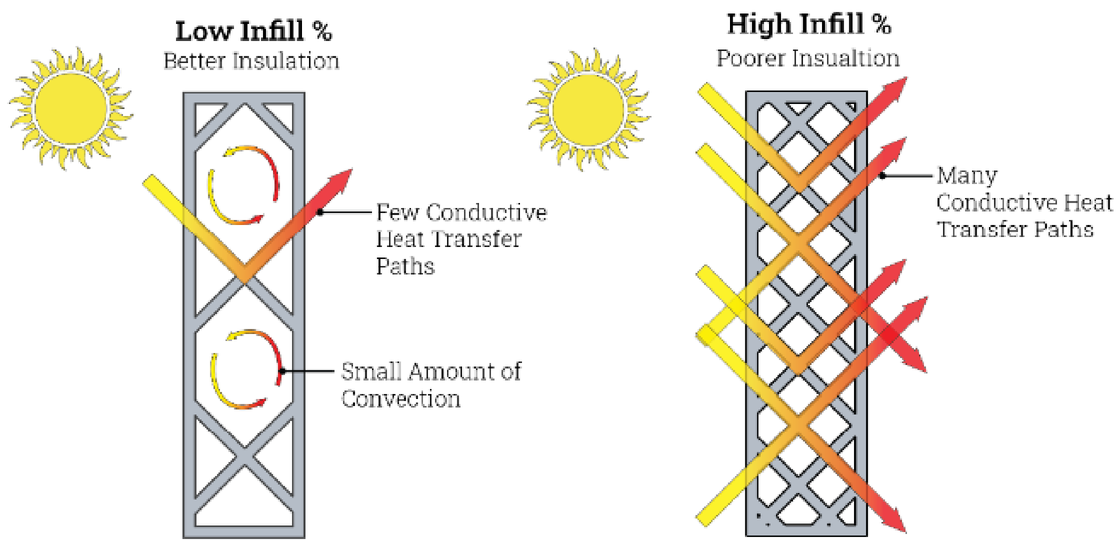


Figure 1.3.4 | A design of 3D printed wall with low infill and high infill.

The results revealed that the thermal resistance properties can be enhanced through topology optimization. Topology optimization enables unnecessary material volume to be removed which entails creating cavities within the wall design rather than being solid. The inclusion of cavities can improve thermal characteristics because the air trapped inside the wall cavities is a poor conductor of heat. Hence air acts as a barrier to heat transfer.[63]

However, the ratio of solid to void inside the wall directly affects the heat conductivity of the wall (Figure 1.3.4). 3D printed objects with lower infill values will provide better insulation for hot climates. Solids, which may convey heat by conduction, are less efficient insulators than air. Higher infill values provide many more conductive paths for heat, which could act as thermal bridges inside the wall. On the other hand, an air gap insulation can only transmit heat through small amounts of radiation or convection.[64] Thus, walls with large, enclosed airspaces uses designed infill density strategy – either thick walls with big spaces inside, low density infill patterns, or both – to provide protection from the hot climate by insulating the space from solar gain.[65]

WASP, an Italian 3D company, has developed a house that is 3D printed using a designed infill density strategy within the wall instead of a totally solid wall (Figure 1.3.5).[66]

63. Andrew Puppos, "Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing,"
64. Andrew Puppos, "Printing Clay: Design Optimization for 3D Printing."
65. Andrew Puppos, "Printing Clay: Design Optimization for 3D Printing."
66. Andrew Puppos, "Printing Clay: Design Optimization for 3D Printing."

Figure 1.3.5 | A 3D printed house in which cavities are designed to enhance thermal properties, TECLA, by WASP.

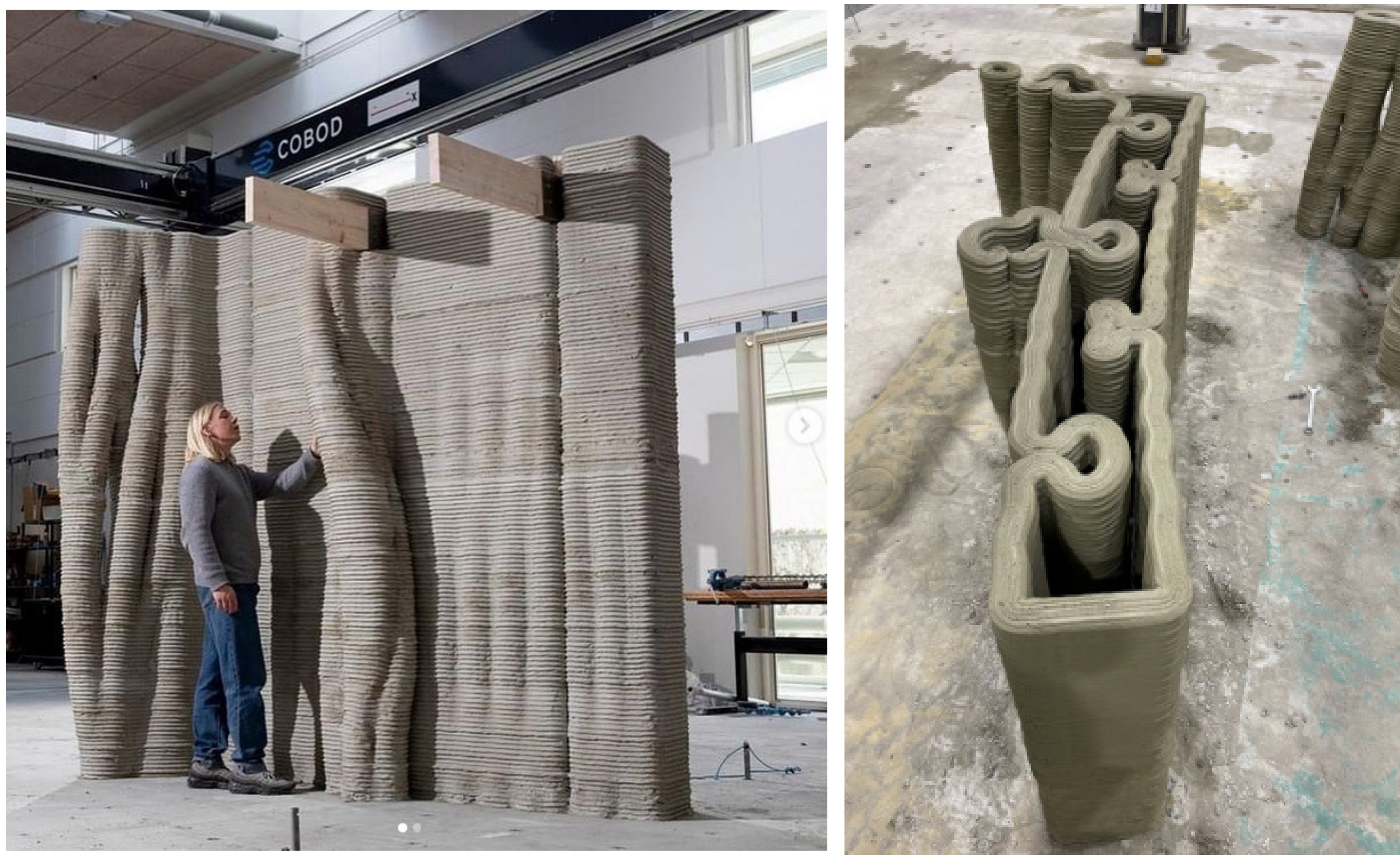


Figure 1.3.6 | Nexus void is a 3D printed wall prototypes with cavities to enhance thermal properties.

However, the wall design is not designed to be thermally effective despite the employment of cavities that exist in the wall design, because there are still certain heat paths that might function as thermal bridges inside the wall.

Nexus Void has provided a design solution that offers no infill within the wall while having a sturdy structure (Figure 1.3.6). In particular, the wall's intricate geometric shape ensures that no thermal bridges occur where heat and cold can escape and that is through the cavity that the wall has.[67] Nexus void uses large cavities to reduce heat transfer while using a buttressing system to provide the wall lateral stability against buckling.[68]

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67. "3D printed wall insulated with sponges," The Royal Academy - Architecture, Design, Preservation," last modified April 5, 2021. https://kglakademi.dk/nyheder/arkitektstuderende-vinder-konkurrence-3d-printet-vaeg-isoleret-med-svampe.
68. "3D printed wall insulated with sponges," The Royal Academy - Architecture, Design, Preservation,".

Chapter 2

Methods

2.1 Overview

The research methodology encompasses designing a brick, with enhanced thermal properties, using Rhinoceros 6 software. The developed brick prototypes are printed using the Potterbot XLS-1 3D clay printer. The printing process involves a computational development phase that uses a “Mesh to Slicer” digital workflow. “Mesh to Slicer” digital workflow consists of 3D modeled meshes generated in Rhinoceros 6 and translated into G-Code via Simplify 3D slicer software. PSH 516 – White stoneware clay is used in this research to fabricate the 3D printed prototypes.

PSH 516 is composed of secondary clays. Secondary clays are transported away from the parent rock by wind or water, unlike primary clays which remain at the physical site where the parent rock decomposed.[69] Secondary clays tend to be much more plastic (a quality of clay that determines its resistance to cracking when bent) than primary clays.[70] PSH 516 was chosen for this research because of its plasticity, and its stability in large-scale work. Moreover, PSH 516 is also classified as stoneware clay that is durable, has high strength and can retain its shape which are important characteristics for brick designs.[71] Once the samples are completed, the 3D printed bricks are tested using THERM software and physical experimentations.

69. Vince Pitelka., *Clay: a studio Handbook*, 4.
70. Diego García Cuevas et al., *Advanced 3D Printing with Grasshopper : Clay and FDM*, 12.
71. Diego García Cuevas et al., *Advanced 3D Printing with Grasshopper : Clay and FDM*, 12.

Figure 2.2.1 | The polycarbonate tube of the Potterbot XLS-1 is attached to the stepper motor.

Figure 2.2.2 | A loaded polycarbonate tube is attached to the 3D printer.

2.2 Fabrication Process

Clay has historically been the most often utilized material in the production of ceramic products such as structural ceramics, used in construction i.e bricks, and technical ceramics, i.e materials with great mechanical, thermal, chemical and electrical resistance.[72] As clay material has evolved, more manufacturing possibilities have developed.[73] The emergence of Additive manufacturing of ceramics enables the exploitation of mechanical properties and high-resolution geometries of ceramic materials, which has not been possible with traditional manufacturing techniques such as injection molding techniques.[74] There are several types of 3D printing ceramics, but none are as commonly used or adaptable as Liquid Deposition Modeling (LDM).[75] LDM is the layer-by-layer formation of objects from a paste material that is extruded by a rotating spindle that regulates the outflow of material.[76] With the emergence of manufacturers such as Potterbot, Lutum, and DetlaWasp, LDM printers have become more commercialized.[77] This research was conducted using the Potterbot XLS-1, a commercially available LDM clay printer. Potterbot XLS-1 is a scara printer, manufactured by 3D potter, with an arm that can extend to 0.9 meters and can rotate in 360 degrees.[78] A threaded rod, connected to a stepper motor, pushes the clay through the polycarbonate tube (Figure 2.1.1). The polycarbonate tube, with a capacity of 3600 ml of clay, is attached to the printer arm (Figure 2.1.2).

72. Carlota V, "Ceramic 3D Printing: A Revolution within Additive Manufacturing?," last modi fied April 16, 2019, https://www.3dnatives.com/en/ceramic-3d-printing-170420194/#!.
73. Carlota V., "Ceramic 3D Printing: A Revolution within Additive Manufacturing?,"
74. Carlota V., "Ceramic 3D Printing: A Revolution within Additive Manufacturing?,"
75. Carlota V., "Ceramic 3D Printing: A Revolution within Additive Manufacturing?,"
76. João Carvalho et al., "Ceramic AM Gantry Structures"
77. Carlota V., "Ceramic 3D Printing: A Revolution within Additive Manufacturing?,"
78. "Potterbot XLS-1," Emerging Objects, accessed October 27, 2022, https://emergingobjects.com/project/potterbot-xls-1/.

A rubber nozzle adapter pushes the clay through a nozzle in a continuous flow. Because of its extensive rotating reach and sturdy extruder components, this printer is suitable for the quick prototyping of ceramic objects.[79]

2.3 Translating Digital to Physical

The typical 3D printing process incorporates digital 3D geometries that are converted to tool paths, or printing instructions, using software that contours geometry according to materiality and function inputs. This software is known as a slicer.[80] Slicers provide a fundamental basis for importing customized print parameters for various printers and materials.[81] This research was conducted using the slicer Simplify 3D in which 3D modeled meshes were imported, and translated into G-Code that can be run by the printer (Figure 2.1.3). The model used the recommended settings provided by Potter, 3D printer manufacturer, to facilitate the printing process. Parameters such as extrusion rate, print speed, and z-axis variability are defined globally in Simplify 3D.[82] Setting these parameters as variables results in prints that better reflect their digital counterparts while reducing unexpected material behaviour.[83] However, there are no parameters in Simplify 3D that can address unpredictable and emergent properties that are characteristic to clay deformation.[84]

79. "Potterbot XLS-1," Emerging Objects,
80. Lucas Carolo, "What is a 3D Slicer?," last modified November 13, 2022, https://all3dp.com/2/what-is-a-3d-slicer-simply-explained/.
81. Lucas Carolo, "What is a 3D Slicer?,"
82. Lucas Carolo, "What is a 3D Slicer?,"
83. Lucas Carolo, "What is a 3D Slicer?,"
84. Benay Gürsoy, "From control to uncertainty in 3D printing with clay,"

2.4 Clay Body Composition and its Working Properties

In this research, one type of commercial clay is used to fabricate the prototypes: PSH 516.

PSH 516 (516) – White stoneware
Material Characteristics:
Cone: 6 Wet Color: Grey
Fire Color Oxidation Cone 6: Creamy White
Texture: Smooth
Average Shrinkage
Oxidation Cone 6: 12,6%
Average Water Absorption
Oxidation Cone 6: 1,5%

Material Ingredients:
Quartz 18.1-24.4
Kaolin Clay >30
Feldspar 7-13
Nepheline Syenite 10-30
Titanium Dioxide 0.3-1.4

Water is added to PSH 516 white stoneware at a weight ratio of 1:40 to facilate 3D printing. This additional water makes the clay easier to extrude. The plastic malleable quality of the clay makes it workable with a wide range of methods and capable of taking on practically any shape as a result.[85] The plasticity of the clay is determined by the size and shape of clay particles. Clays with higher plasticity are the ones with the lowest particle size.[86]

85. Vince Pitelka., *Clay: a studio Handbook*, 4.
86. Vince Pitelka., *Clay: a studio Handbook*, 4.

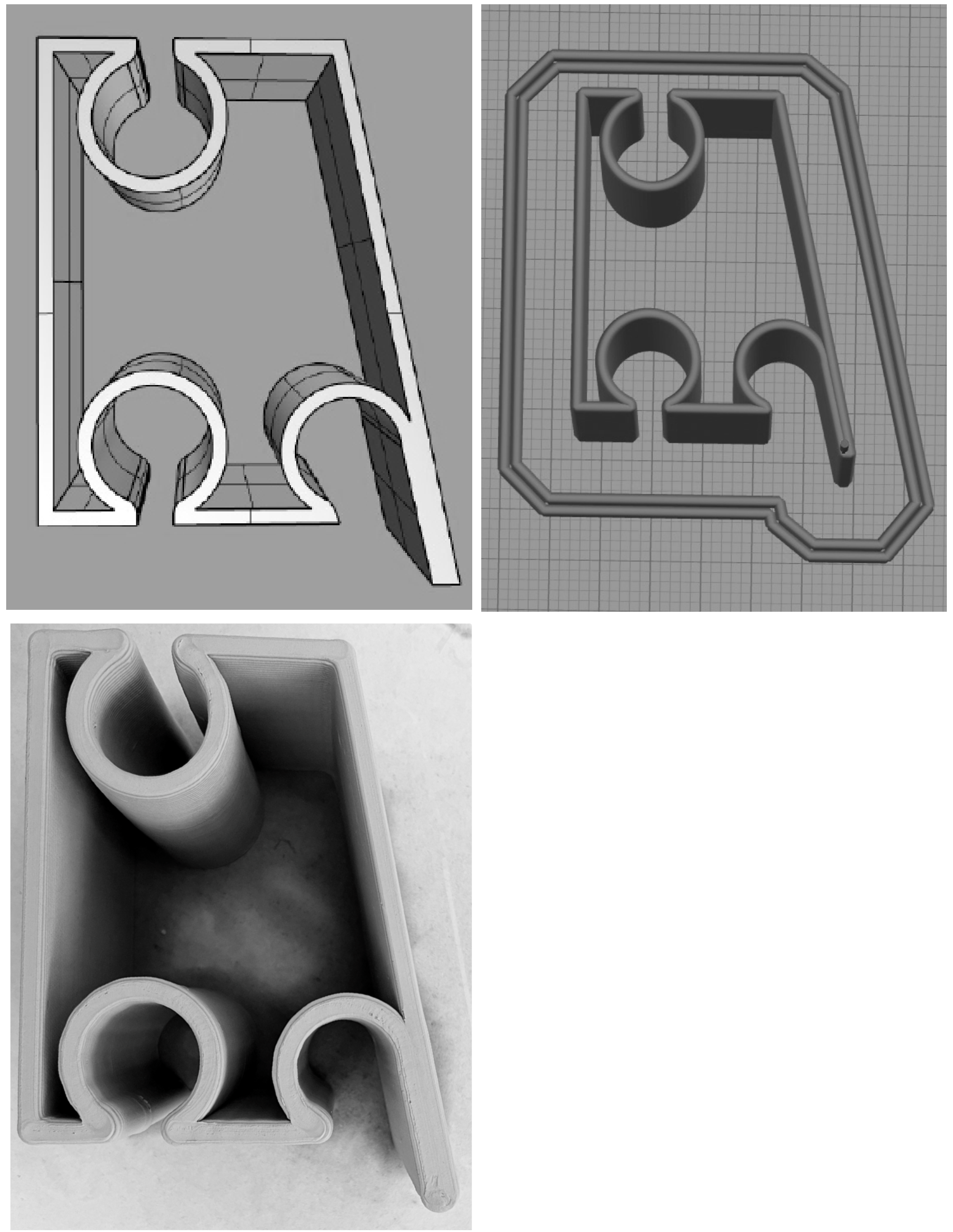


Figure 2.3.1 | Workflow from digital geometry produced in Rhino (top left), to tool path generated via Simplify 3D, slicer software (top right), to physical print (bottom left).

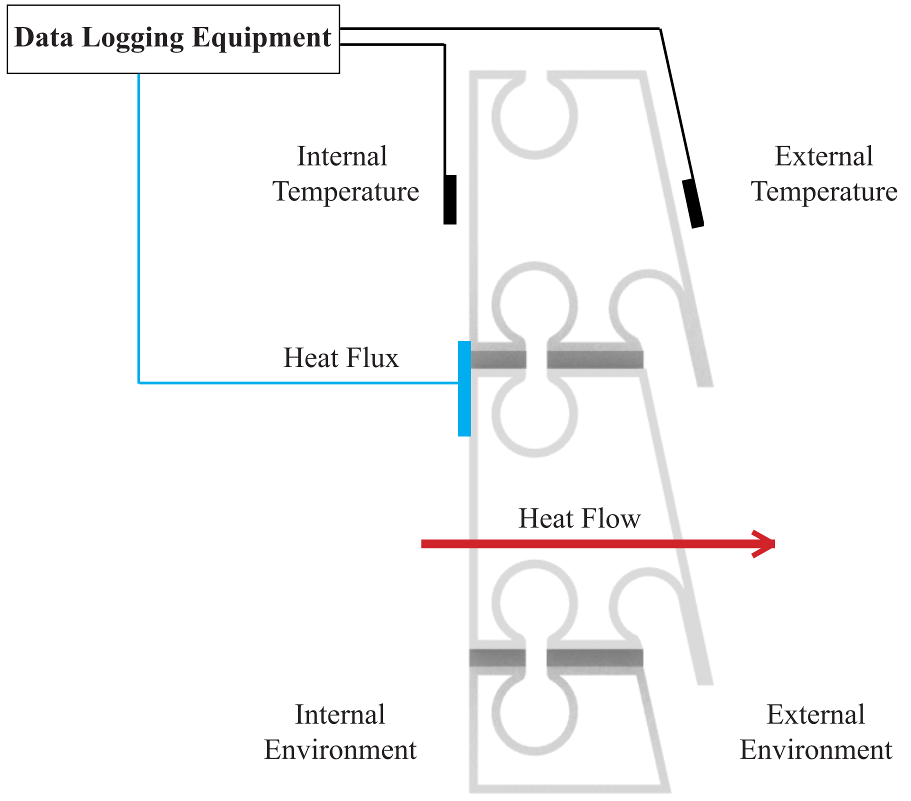
2.5 Thermal Assessing Methodology

To assess the thermal properties of a brick, this research adopts the method of using U-values. U-value is a method of assessing the heat flow or heat loss that occurs through the material due to the difference between indoor and outdoor temperatures.[87] (Figure 2.1.4). Designing a brick wall with low thermal conductivity is essential in developing low energy consumption structures that consume less energy to keep enclosed regions comfortable.[88] (Figures 1.3.4 and 1.3.6) Heat flows faster through materials with a higher thermal conductivity.[89] On the other hand, a lower u-value indicates an enhanced insulating performance. To evaluate the design of the 3D printed brick wall in this thesis, the u-value will be calculated using THERM software and physical experimentations.

2.5.1 Digital Simulations Overview

THERM is a two-dimensional heat-transfer modeling software tool for buildings. The program, developed at Lawrence Berkeley National Laboratory (LBNL), can be used to simulate two-dimensional heat-transfer effects in building components like windows, walls, foundations, roofs, doors, appliances, and other products where thermal bridges are a concern.[90] It is a type of mathematical modeling used to evaluate heat transfer resistance because it is feasible to estimate the integral properties (averaged heat flux over the surface, etc.) more accurately than

87. Milad Mahmoodzadeh et al., “Determining overall heat transfer coefficient (U-Value) of wood-framed wall assemblies in Canada using external infrared thermography,”
88. Rafikullah Deraman et al., “Improving thermal conductivity of fired clay brick using sawdust waste,”
89. Rafikullah Deraman et al., “Improving thermal conductivity,”
90. “THERM software,” Windows Daylighting, accessed October 28, 2022, https://windows.lbl.gov/software/therm.



$$U = \frac{\sum q}{\sum (T_i - T_e)}$$

q – density of heat flow arte, W/m2;
Te- external air temperature, °C or K
Ti- external air temperature, °C or K

Figure 2.5.1.1 | A diagram that illustrated the equation of the U-value method.

in an experiment, where these values can only be determined at monitoring sites.[91] THERM software is utilized in this research to evaluate the energy efficiency of 3D printed clay bricks using the u-value computation and thermal pictures of the design. The exterior and interior boundary conditions in this research are set to 40 degrees and 10 degrees Celsius (°C) respectively. The temperature range is increased to allow substantial temperature difference between inside and outside environments. Increasing the temperature ranges of the environments will investigate the insulation properties of the brick and will show the effect of thermal conductivity on the thermal images and u-value. Thermal Conductivity of each material used in this research are provided by the author:

1- Clay	1 W/m-k
2- Mortar	1.8 W/m-k
3- Polyurethane foam	0.05 W/m-k
4- Air	Frame Cavity

The digital simulations began with a solid brick to determine how each design step increasingly improves the thermal characteristics of the 3D printed bricks, through the calculation of each step's u-value. The u-value calculated by THERM for each of the design steps will be compared to the u-value of the solid brick as a bench mark to prove how each of the design steps has a direct impact on the improvement of the thermal properties.

91. Nemova et al., "Experimental Study on the Thermal Performance of 3D-Printed Enclosing Structures,"

The lower the u-value, the better insulated is the brick. Apart from the u-value, the results will also include thermal images of each step. The brighter colors red, orange, and yellow indicate warmer temperatures due to the radiated heat and infrared radiation. Purples, dark blues, and black represent colder temperatures because less heat and infrared radiation is released. [92] The various color tones correspond to the brick's apparent surface temperatures.

2.5.2 Case Studies and Physical Experimentations

Physical experiments are also an important tool to assess the wall's thermal effectiveness. Previous works have looked at assessing the thermal conductivity of 3D printed wall samples. Puppos addressed how to evaluate the printed samples and built a testing apparatus. The testing apparatus consists of two nested boxes of 1" foil faced insulation foam, separated by a 1.4" air gap.[93] To seal the boxes and ensure their airtightness, expanding foam was employed. For each sample, a foam frame was cut and fastened within the frame utilizing expanding foam and silicone caulk. A DHT11 temperature sensor within the box monitored the ambient air temperature.[94]

To monitor the surface temperature of each sample, a 10k thermistor was attached to its inner surface.

92. "Understanding Thermal Palettes," Thermascan,"accessed October 13, 2022, https://www.thermascan.co.uk/blog/thermal-palettes.
93. Andrew Puppos., "Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing."
94. Andrew Puppos., "Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing."

For the course of each test period, an Arduino data logger took readings at 30 second intervals. For maximum sun exposure, the apparatus was positioned outside in full sunshine at a 45-degree angle (Fig. 2.5.2.1).[95] Over three days with nearly identical weather conditions, data was gathered from sunrise to sunset, or roughly 12 hours total.

Prasittisopin et al. designed another testing apparatus in which each panel was built and sealed in a foam insulation cabinet facing south (Figure 2.5.2.2).[96] The surface temperatures of both the inner and exterior walls were measured every 10 minutes with a thermocouple inserted in the middle of each panel and a data logger. The apparatus has a measuring range of 10 °C to 200 °C with an accuracy of 0.5 °C or 0.5%.[97] Data was collected for around three days. Temperatures on three days were averaged over a 24-hour period. Meanwhile, the temperature of the outside air (ambient) was monitored.

95. Andrew Puppos., “Printing Clay: Design Optimization for 3D Printing Sustainable and High-Performance Housing,”
96. Lapyote Prasittisopin et al., “Thermal and Sound Insulation of Large-Scale 3D Extrusion Printing Wall Panel,”
97. Lapyote Prasittisopin et al., “Thermal and Sound Insulation of Large-Scale 3D Extrusion Printing Wall Panel,”

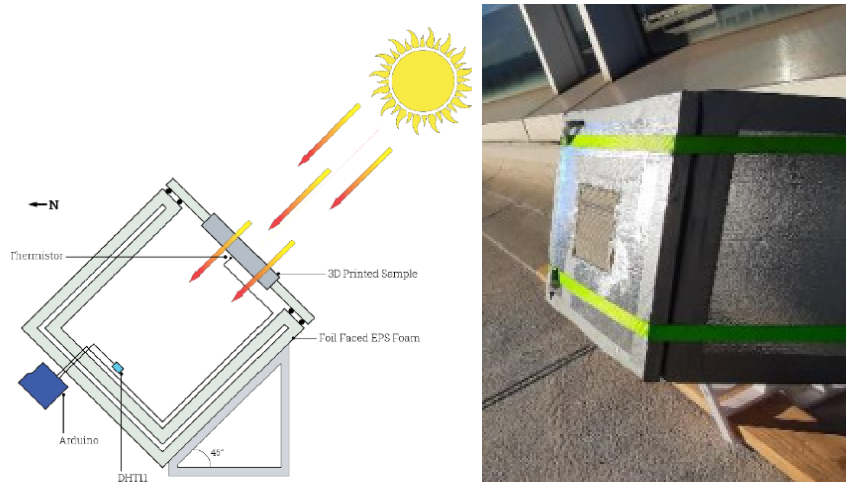


Figure 2.5.2.1 | A precedent for an apparatus setup that evaluates the thermal effectivness of a wall design panel.

Figure 2.5.2.2 | Phyiscal experiment precedent to measure the effect of texture on enhancing thermal properties.

Chapter 3

Research Development

3.1 Comparison of Traditional Solid Brick to Hollow Brick

Clay bricks are traditionally made in a solid shape with no cavities.[98] The construction industry has provided solutions for enhancing thermal properties of a brick over the years by developing cavities in the individual brick for air to be trapped inside them, as trapped air is a poor conductor of heat. However, despite the use of cavities in the design, some of these solutions are not designed to be thermally effective because certain heat paths may still function as thermal bridges inside the wall. Additionally, cavities in the brick are filled with mortar when bricks are stacked. Mortars solidify and function as a thermal bridge through heat conduction (Figure 1.2.1.4.2). In this research, additive manufacturing (3D printing) is used to design the geometry of cavities within a brick. Subsequently, the thermal properties of the brick can be enhanced by designing its air cavities.

THERM, the heat analysis tool, was used to investigate the thermal performance of the proposed 3D printed brick in comparison to other bricks that exist in the construction field, for example, solid bricks, engineering bricks with cavities, and German Proton bricks. To make a fair comparison, the dimensions of the bricks were kept the same as well as the boundary conditions set in the software. According to the findings, the proposed 3D printed brick has achieved the lowest u-value among the construction brick designs.

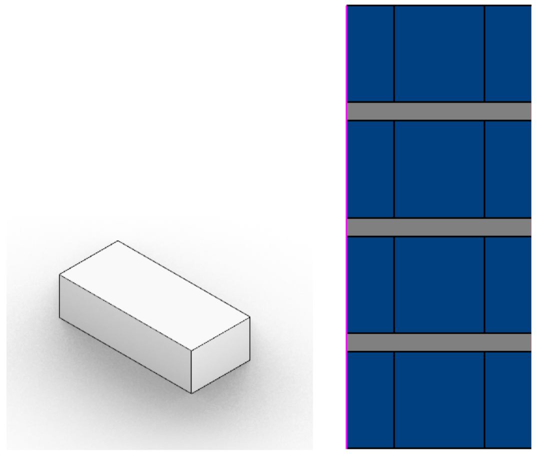
98. Ahmed S. Al-Tamimi et al., "Effect of geometry of holes," 3734.

The 3D proposed printed brick does not provide heat paths for heat to travel through and it achieves the superior thermal performance (Figure 3.1.4). On the other hand, the construction bricks (solid brick, German brick, and engineering brick) use mortar between consecutive bricks during stacking. Consequently, the mortar moves into the bricks' cavities and solidifies. Since, mortar is a good conductor of heat, it acts as a thermal bridge, and thus reducing the thermal efficiency of the bricks.

In addition, mortar has a thermal conductivity value of 1.8 W/m2-k, which increases the overall thermal conductivity of the brick (Figure 3.1.2). Subsequently, the u-values associated with the different designs are impacted by the relative proportion of mortar to clay. For instance, the engineering brick (with mortar fully filled inside its cavities) has the highest u-value of 3.90 W/m2-k. Depending on the proportion of mortar in the design, the bricks in figure 3.1.1 and 3.1.2 follow a logical order of thermal performance (from best to worst thermal performance): Ubrick+air (3.18 W/m2-k) < Ubrick+air+mortar (3.54 W/m2-k) < Ubrick (3.65 W/m2-k) < Ubrick+mortar (3.90 W/m2-k) (Figure 3.1.2).

THERM was used to find the u-values associated with the German brick with and without the insulation. According to the simulations from THERM software, the German Proton brick has a u-value of 2.41 W/m2-k when filled with air only, and u-value of 1.66 W/m2-k when filled with polyethylene foam (Figure 3.1.3). Compared to the 3D printed brick proposed in this research, the German bricks have higher u-values. This follows since the German brick has heat paths that functions as thermal bridges inside the wall. Additionally, the German brick design (without the insulation) has cavities in which mortar can fill them and becomes inefficient thermally and acts as a thermal bridge.

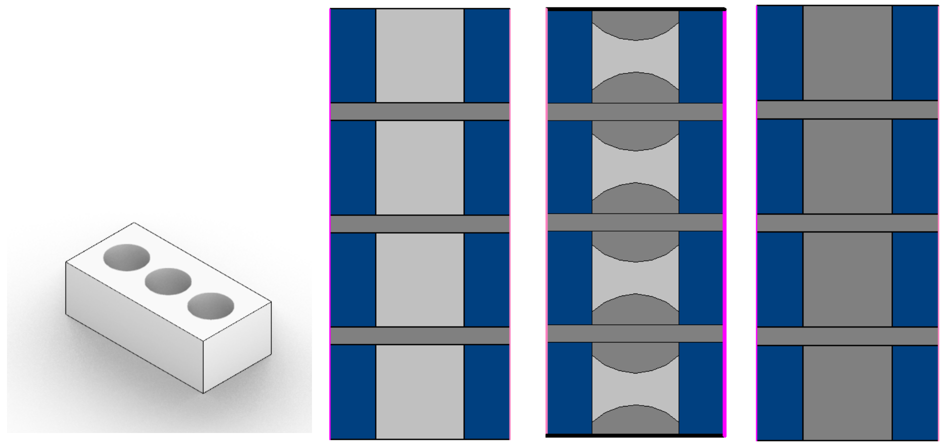
The research also has used to test the thermal performance of the proposed 3DP brick with the insulation filling. Polyethylene foam with the thermal conductivity of 0.05 W/m2-k was used to fill the proposed brick design. The results have shown a low u-value of 1.00 W/m2-k when compared to both an earlier step of the proposed design of 2.88 W/m2-k (see Figure 3.2.1) and a final stage of the design without the insulation filling of 2.35 W/m2-k (Figure 3.2.5). Moreover, in the construction industry, the brick cladding function is typically decoupled from the insulation function.



Traditional Clay Brick

U-value = 3.6503 W/m2-k

Figure 3.1.1 | Measuring the u-value of solid clay brick.



Engineering Brick with 3 cavities

Ubrick+air = 3.1779 W/m2-k

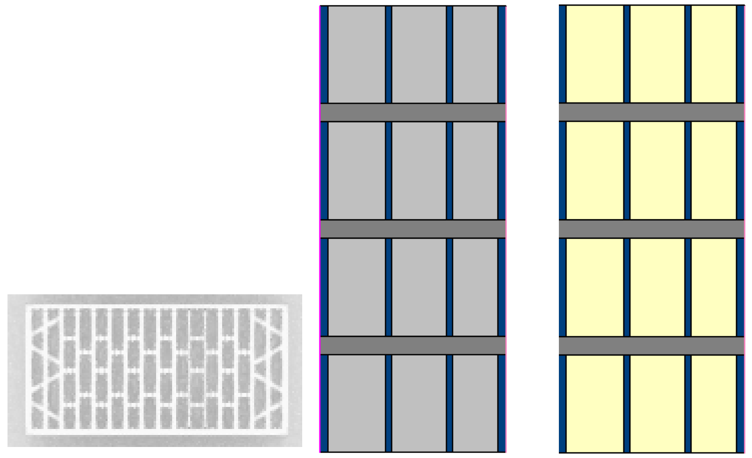
Ubrick+air+mortar = 3.5394 W/m2-k

Ubrick+mortar = 3.8971 W/m2-k

Figure 3.1.2 | Measuring the u-value of engineering brick with 3 cavities.

In contrast, this research joins the brick cladding function with the insulation function through conducting digital simulations. This follows as combining the brick cladding and the insulation reduces the construction costs in hot climatic zones.

The previously discussed digital simulations were to assess the thermal effectiveness of the proposed brick design in comparison to other existing bricks in the construction field (via the digital simulations in Figures 3.1.1, 3.1.2, 3.1.3 and 3.1.4). However, the rest of this chapter discusses preliminary studies of the proposed 3D printed bricks, followed by the proposed brick design development. This chapter then illustrates how the developed 3D printed brick can be integrated into a wall system, that in addition to enhancing thermal properties, provides shade and acts as an optimized rainscreen.

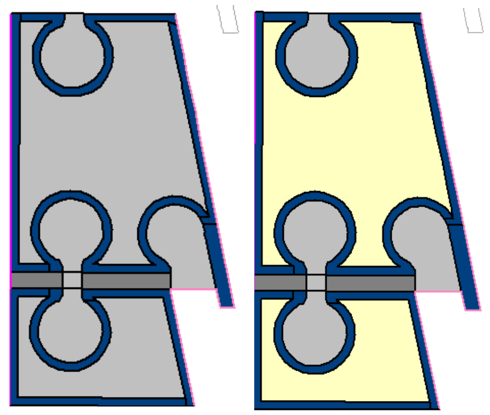


German Proton brick

Ubrick + air = 2.4116 W/m2-k

Ubrick + polyethylene foam = 1.6529 W/m2-k

Figure 3.1.3 | Measuring the u-value of German brick.



Enhanced Thermal brick

Ubrick + air = 2.3524 W/m2-k

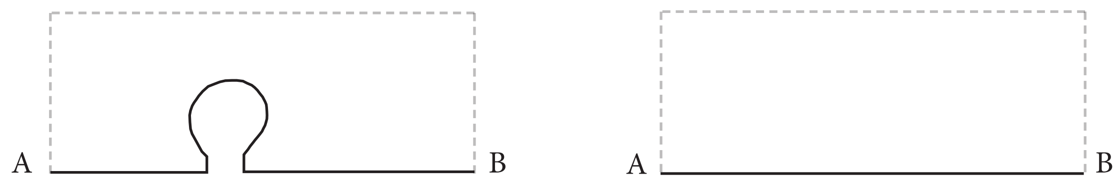
Ubrick + polyethylene foam = 1.0014 W/m2-k

Figure 3.1.4 | Measuring the u-value of this research’s brick design.

3.2 Preliminary Studies of Designed Hollow Bricks

The iterations in this section were mainly based on the concept of heat flow. Heat flow is the movement of heat energy from one point to the other. For the purpose of this study, heat path delay effect refers to loops (defined here as thermal loops, which are circular subtractions from the profile brick) that are designed to increase the distance that the energy transfer path completes between Point A and Point B and thus reduces heat transfer (Figure 3.2.1). On the other hand, heat energy travels through a traditional brick in a straight line from point A to point B and thus increase the heat transfer rate (Figure 3.2.1). While the digital and physical thermal experiments were not conducted at the individual brick level, the thermal performance of the wall system will be studied in detail as described in Section 3.3.

The first set of tests primarily investigates the effect of air cavities on the heat flow by testing various geometry variations in an individual brick. The variations include the circular thermal loops, their size, placement within the brick boundaries, and the frequency with which they occur within a brick. Indeed, air cavities are a primary aspect in this research because air trapped inside them is a poor conductor of heat, and therefore, air acts as a barrier to heat transfer. Thermal loops, being secondary elements, help to increase the distance that the energy transfer path completes between the interior and exterior of the wall and thus, reduce heat transfer. Subsequently, the initial experiments were



The Direction of the Heat Transfer Path from Point A to Point B

The Direction of the Heat Transfer Path from Point A to Point B in the traditional solid brick

Figure 3.2.1 | The diagrams illustrate the that the loops designed increase the time heat takes to travel from point A to point B (left) in comparison to a traditional brick (right).

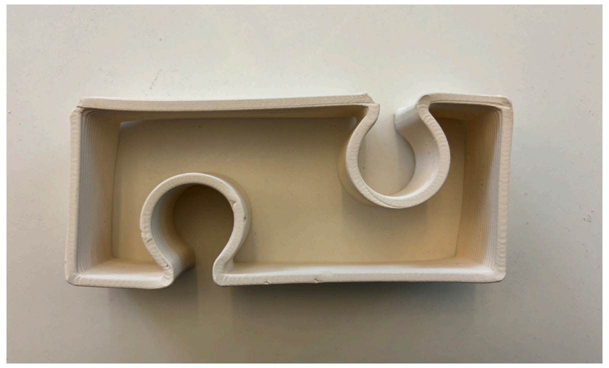


Figure 3.2.2 | Module 1

Figure 3.2.3 | Module 2

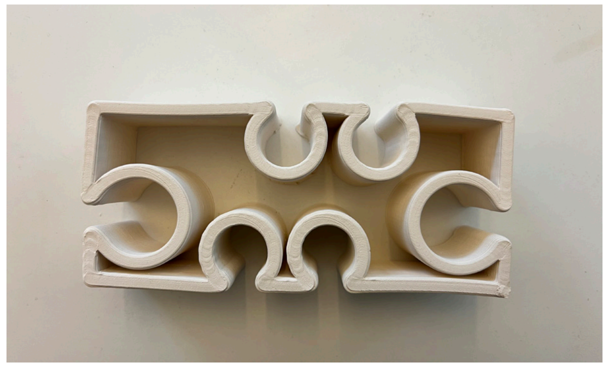


Figure 3.2.4 | Module 3

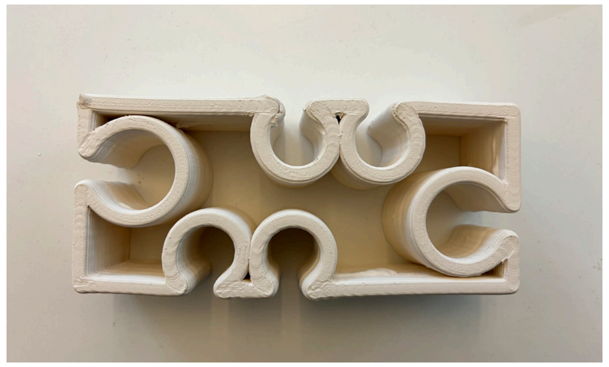


Figure 3.2.5 | Module 4

Figure 3.2.6 | Module 5

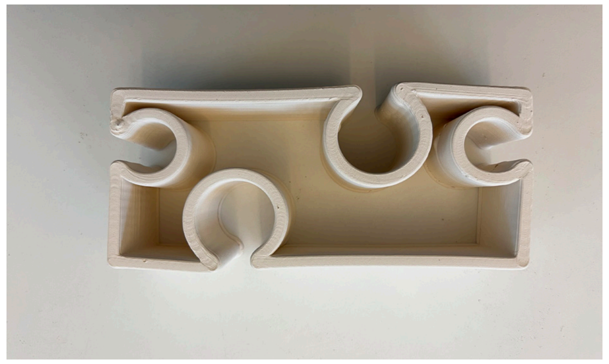


Figure 3.2.7 | Module 6

conducted not to test the thermal performance of the geometry, but rather to study the size and ratio between air cavities and the brick.

In Module 1, a void infill (or the internal structure of the brick) was implemented to block any heat paths from transferring heat across the brick (from one side of the brick to the other side). Moreover, two circular loops were placed along the longest sides of the brick to to increase the distance that the energy transfer path travels between the interior and exterior of the wall, reducing heat transfer. In order to maintain the brick balance in terms of weight and stability, the loops were placed to face alternate directions.

In Module 2, the brick was designed with four semi-circular loops that were placed to face alternate directions to each other. However, the semicircular loops were not as efficient as the circular loops in increasing the travel time of the heat energy across the brick. Hence, the circular shaped loops were considered for the rest of the experiments.

Modules 3 and 4 were designed to include two different sizes of circular thermal loops. In particular, as shown in Figures 3.2.4 and 3.2.5, two smaller circular loops were placed along the longest side of the brick and one bigger loop was placed along the

brick's shortest side. While in Module 3, the bigger loops were placed opposite to each other, in Module 4 the bigger loops were placed on alternate sides. While Modules 3 and 4 had the smaller loops on the longer side of the brick, Modules 5 and 6 were designed to have smaller loops on the shortest side. Particularly, Module 5 had smaller loops on alternate direction to each other and Module 6 had smaller loops opposite to each other.

The previous preliminary experiments considered the design of inside cavities (that trap internal air) and outside cavities (that trap external air. For the rest of this thesis, the brick design development focuses on only the incorporation of inside cavities (inside thermal circular loops). This follows, as trapping (external) air in the external cavities reduces the thermal insulation properties of the brick (by bringing the external air closer to the section of the brick).

3.3 Brick Design Development

This section discusses the development and the evaluation of the thermal performance of the proposed 3D printed brick. The evolution of a brick design, from a solid to a thermally enhanced brick, is then illustrated. Moreover, the thermal performance of different brick designs will be evaluated by comparing the corresponding u-values calculated using THERM.

THERM software was used to evaluate the energy efficiency of 3D printed clay bricks using the u-value computation and thermal pictures of the design. The software proves how each for the design steps has a direct impact on the improvement of the thermal properties of the proposed design.

Step 1 shows solid clay brick that has a u-value of 2.88 W/m2-k. Step 2 shows hollow brick with 50mm wall with lower u-value of 2.77 W/m2-k. The decrease in the u-value, that happened as a result of removing the solid material, proves that the inclusion of cavities can improve thermal characteristics, as the air trapped inside the wall cavities is a poor conductor of heat. Hence air acts as a barrier to heat transfer.

Figure 3.3.3 includes an overlapping lip that extends to overlap with the brick beneath it. The introduction of overlapping lip in step 3 reduced the u-value to 2.53 W/m2-k because the overlapping lip has a loop that reduces the direct path of energy transfer

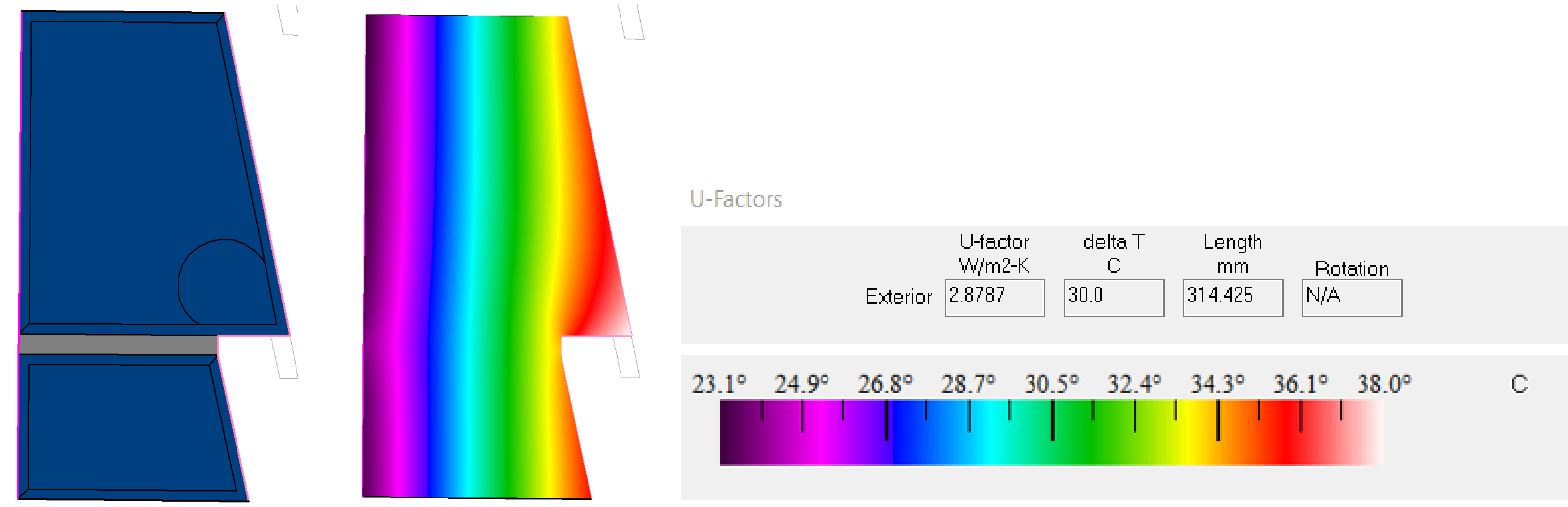


Figure 3.3.1 | Step 1 | Solid brick.

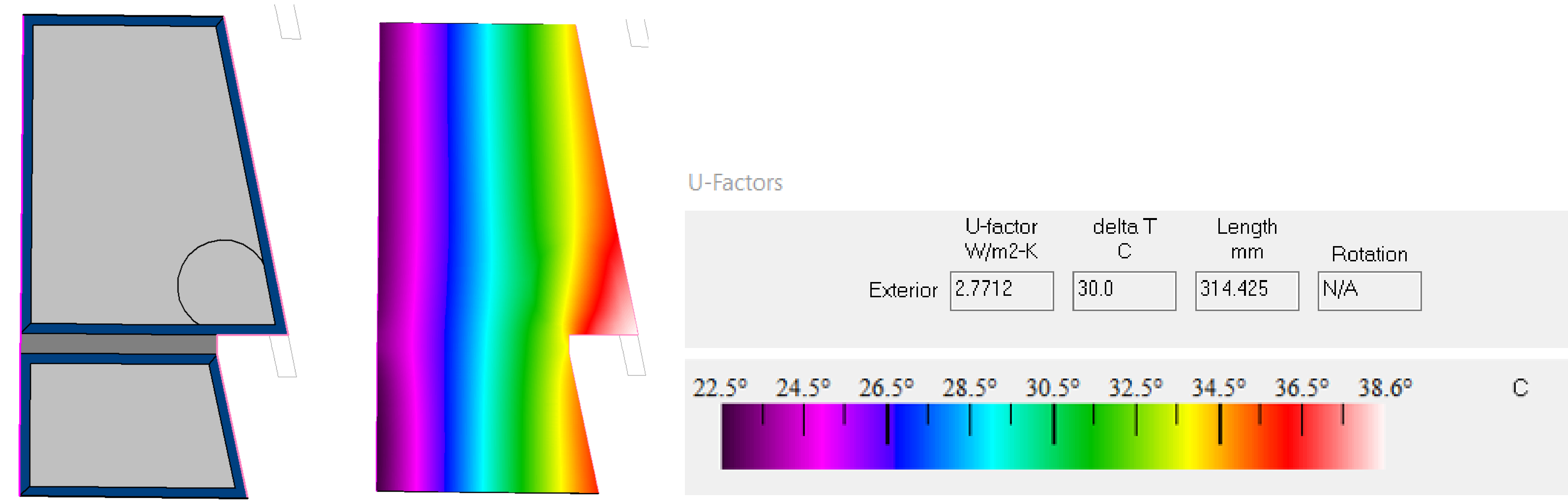


Figure 3.3.2 | Step 2 | Carving out the brick.

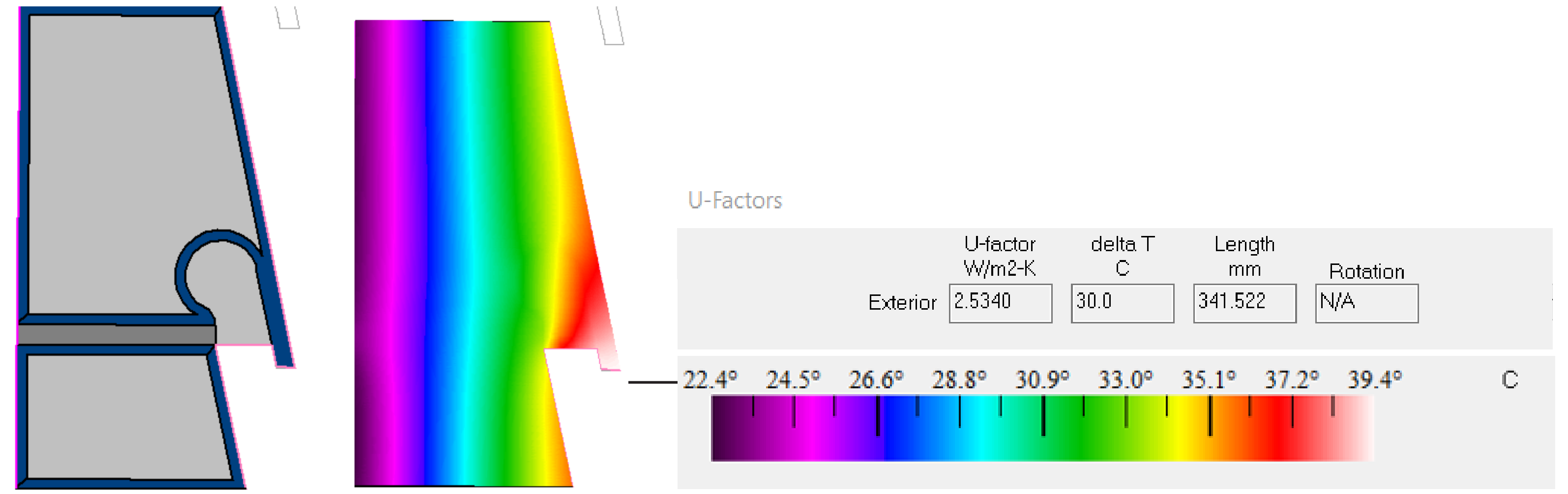


Figure 3.3.3 | Step 3 | Introduction of the overlapping lips.

between the exterior and the interior. The overlapping lip also provides self-shade, which keeps the brick system cool and thus reduces heat transfer.

Step 4 introduces additional loops, defined here as thermal loops, which are circular subtractions from the profile brick (shown in Figure 3.3.4). Thermal loops increase the distance that the energy transfer path must travel between the interior and exterior, resulting in a lower u-value of 2.40 W/m2-k. The design of the thermally enhanced 3D printed clay bricks has taken into account the design of the mortar in step 5 between consecutive bricks. Mortar, being solid, is a good conductor of heat, thus placing mortar between consecutive bricks blocks the thermal loops and result in a thermal bridge. Hence, the mortar has been placed in only the solid parts between consecutive bricks, which results in a lower u-value of 2.35 W/m2-k.

The research has also considered filling the brick with an insulation material instead of air cavity. Polyethylene foam with the thermal conductivity of 0.05 W/m2-k and Perlite with the thermal conductivity of 0.0530 W/m2-k were chosen to fill the brick at step 6 of the design. The results have shown a significant low u-value of 1.00 W/m2-k when compared to both solid brick of 2.88 W/m2-k and step 5 of the design of 2.35 W/m2-k.

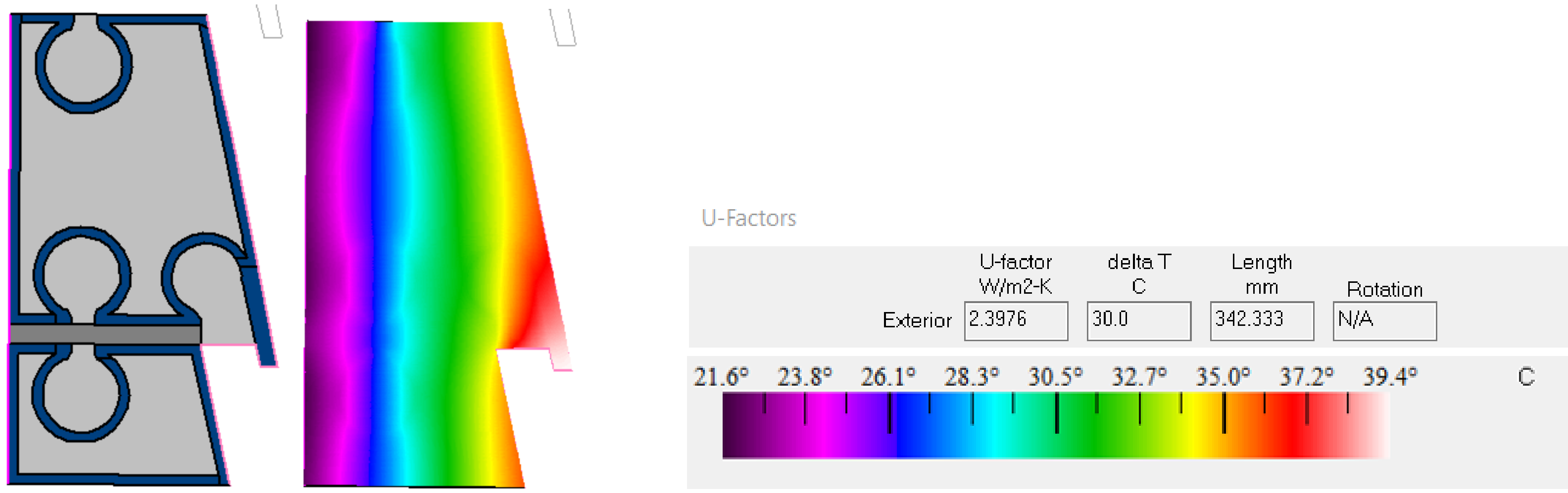


Figure 3.3.4 | Step 4| Introduction of circular thermal loops.

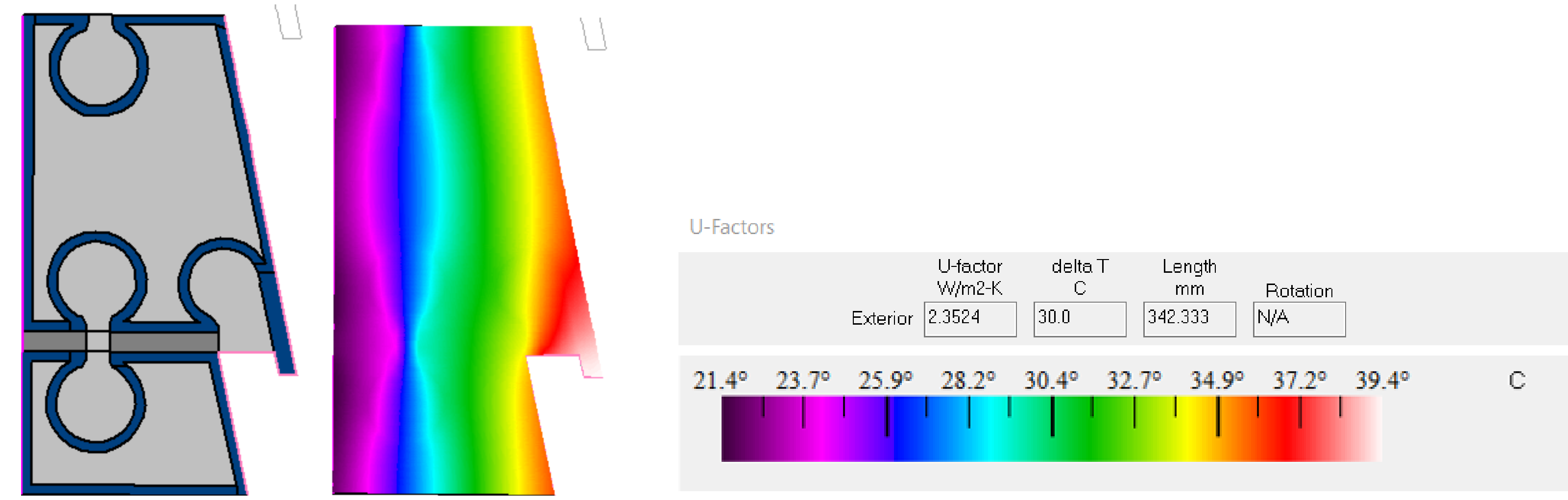


Figure 3.3.5 | Step 5 | Design of mortar.

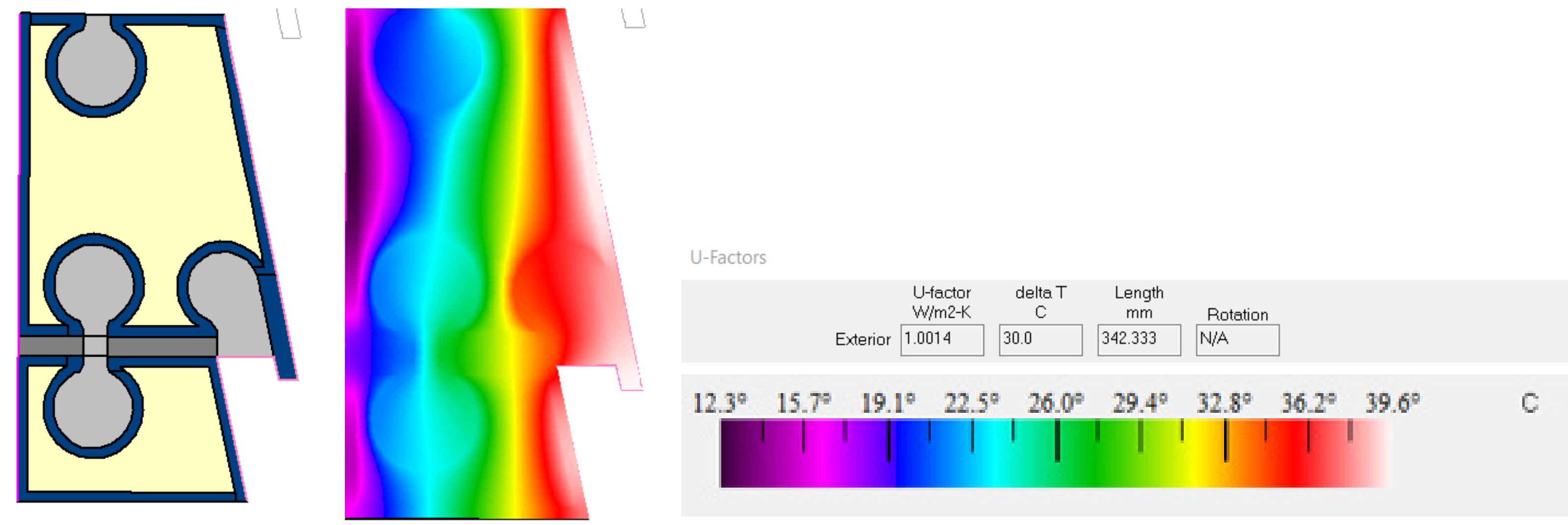


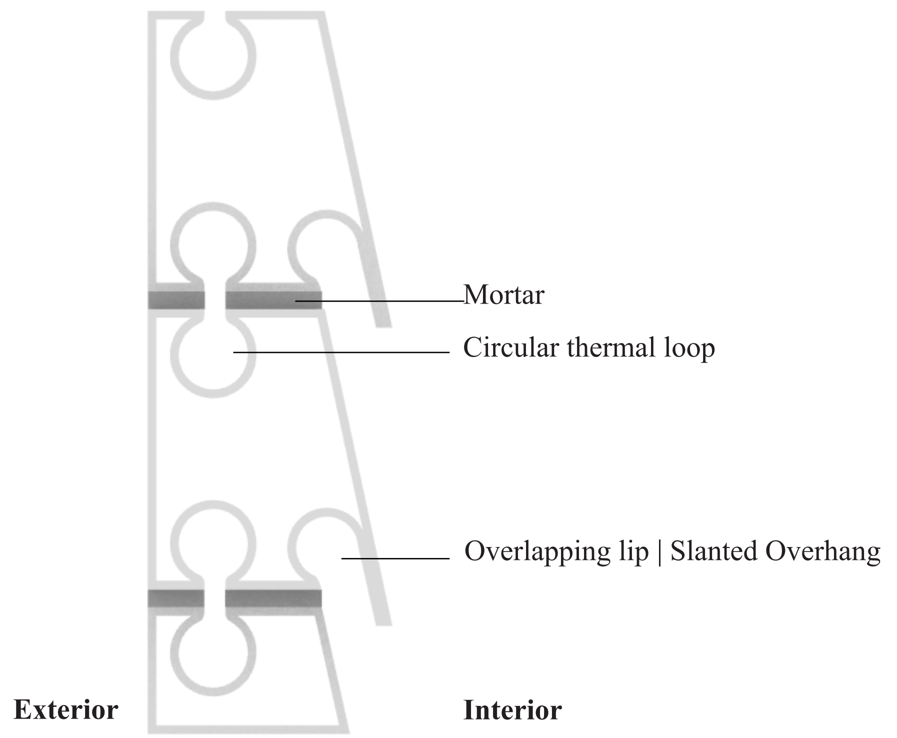
Figure 3.3.6 | Step 6 | Introduction of insulation, polyethylene foam, 0.05 W/m2-k.

The Temperature Range Comparison

When the temperature ranges of steps 1, 5 and 6 are compared, the results reveal that the best performing design has a greater temperature difference, as seen in step 6 where both the inside and outside surface temperatures are close to the original temperature setting of 10 and 40 °C. In step 1, the interior surface temperature of the solid brick is 23.1 degrees, and the exterior surface temperature is 38 °C. Step 5 of the brick design has a better temperature range of 21.4 °C and 39.4 °C. Adding insulation fill has significantly increased the temperature range to 12.3 °C and 39.6 °C. This is a significant improvement because this temperature range is close to the original set temperatures of the simulations. Both surface temperatures of step 6 bricks have a little change which means that adding insulation has improved the thermal conductivity of the brick.

3.4 Wall Design Development

The second step of the research implements similar concepts of the initial design experiments while maintaining the heat path delay effect that is described in detail in Section 3.2 (Figure 3.2.1). In particular, the design of mortar between consecutive bricks has been considered to only be placed in only the solid parts between consecutive bricks as shown in Figure 3.4.1. Otherwise, the mortar fills in the designed thermal loops, acts as a thermal bridge and accelerates the rate of heat transfer. The external design of the brick also includes an overlapping lip or a slanted overhang, that has a thermal loop which reduces the direct path of energy transfer between the exterior and the interior.The overlapping lip also creates a shading area that helps in providing coolness to the interior because the brick is partially protected from continuous sun exposure. To enhance the stability of the wall system, the third step of the design staggered the subsequent bricks rather than stacking them on top of one another (Figure 3.4.2). Bisque fired 3D printed clay bricks had been stacked using a rubber sealant. Rubber sealant, performing better than mortar, helps to trap air using its molecular structure, resulting in having a lower u-value, and thus enhances the thermal performance of the overall brick system (Figures 3.4.3 (a) and (b)).



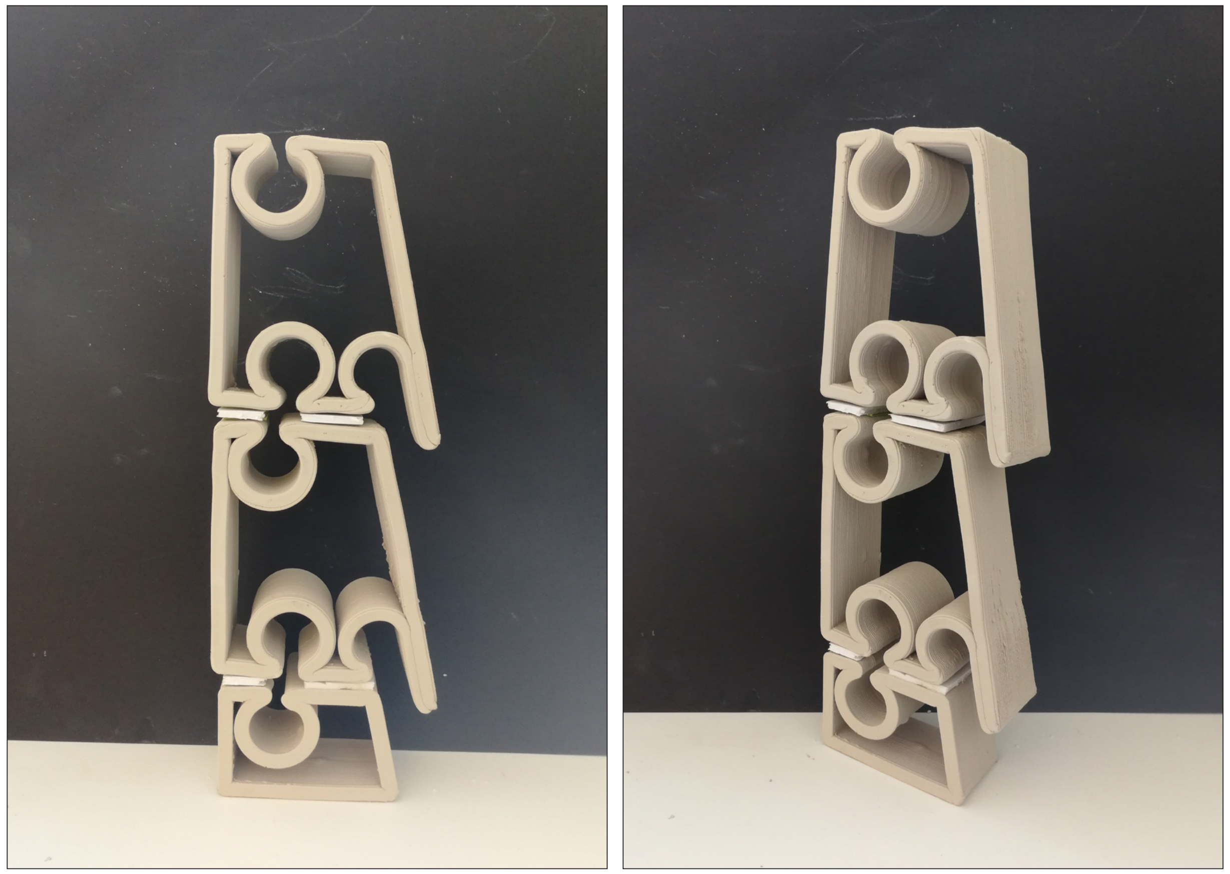


Figure 3.4.1 | The diagram illustrate the development brick system (top), The images demonstrate the placement of mortar within the developed proposed geometry.

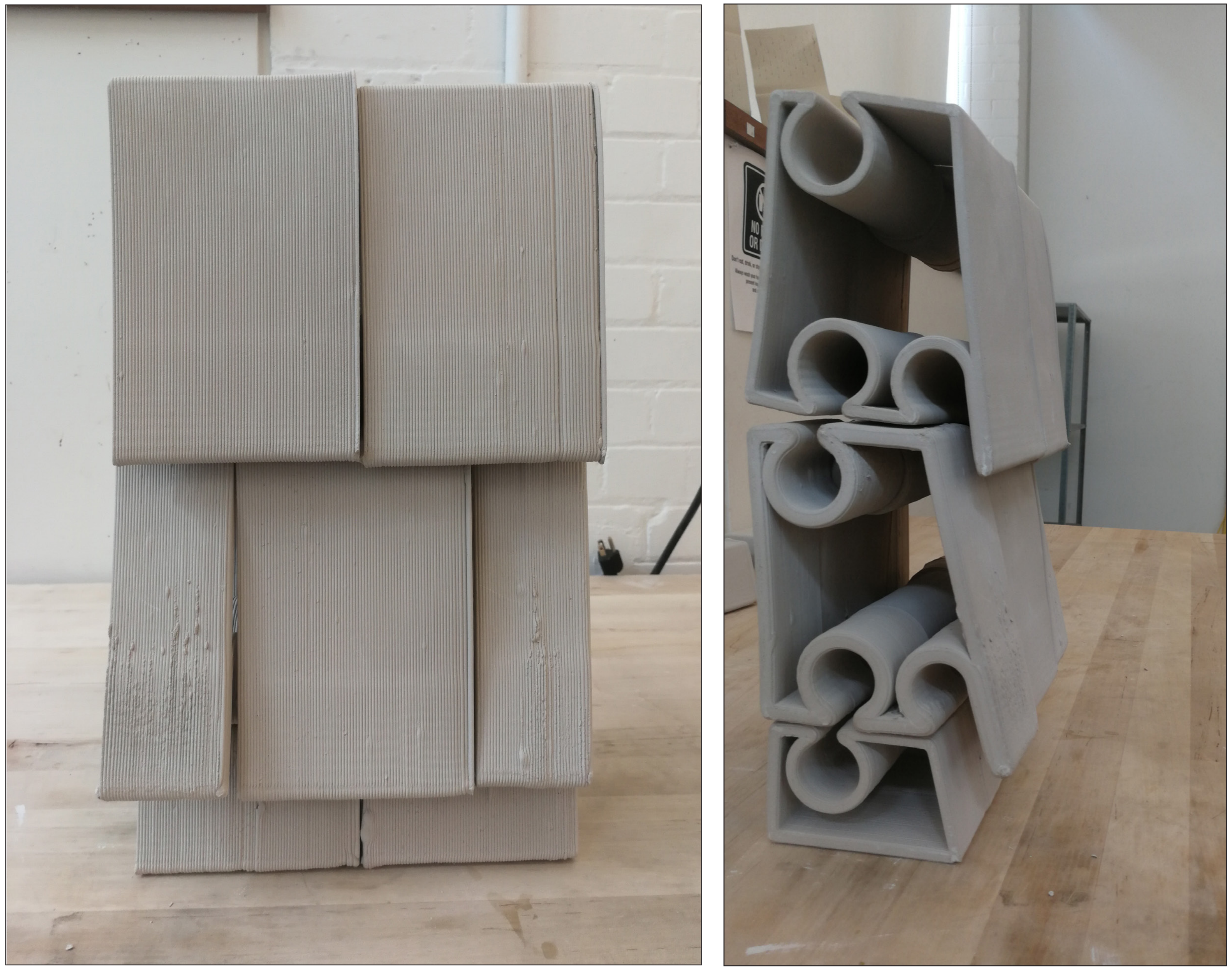


Figure 3.4.2 | The proposed geometry are staggered at this stage instead of being stacked to achieve stability of the bricks.

Figure 3.4.3 (a) | Bisque fired 3D printed clay bricks are stacked using a rubber sealant.

Figure 3.4.3 (b) | Bisque fired 3D printed clay bricks are stacked using a rubber sealant.

3.5 Physical Experiment Testing of the Proposed Wall

The thermal effectiveness of the wall, proposed in the previous section, will also be assessed by conducting a physical experiment in this section.

The physical experiment will be conducted using the setup illustrated in (Figure 3.5.1 and 3.5.2). In particular, a commercially available wireless thermometer with a temperature sensor and a data logger are used to monitor the surface temperature of the bricks at 10-seconds intervals. Meanwhile, the temperature of the outside air (ambient) was monitored and kept constant at 21 °C.

A testing apparatus is created in which the wall is enclosed by a 50 mm thick Xps foam (Figure 3.5.1). The Xps foam is a closed cell foam. The R-value per inch of the foam used in this research is R-5. Using 2 inches of this foam for the physical experiment results in an R-value of R-10. To seal the insulation box and ensure its airtightness, framing aluminum foam tape was employed at the inner edges that connect the brick and the foam.

This research developed an experimental procedure to assess the thermal properties of the proposed design as illustrated in Figures 3.5.2. The purpose of this experiment was to prove that the geometries developed in the brick's internal structure (or the

Figure 3.5.1 | Physical experiment setup.

infill) improved the thermal properties of the brick. In particular, in the physical experiment, one temperature probe was placed at interior side of the exterior wall to measure the surface temperature before the infill (the geometry of brick's cavity, the thermal loops and the overlapping lips) (Figure 3.5.2). On the other hand, another probe was placed on the surface of the interior wall after the infill. Therefore, data was collected before and after the infill to evaluate the impact the geometry had on the thermal effectiveness of the brick (Figure 3.5.2).

A source of heat was placed at a 1-meter distance away from the apparatus. With no source of heat placed inside the setup, the thermal performance was tested by measuring the time it took for the temperature inside the setup to reach the temperature on the outside. The results of the experiment were demonstrated through graphs that illustrated the time interval (in seconds) in relation to the temperature change in degrees Celsius (°C).

Graph in Figure 3.5.3 shows the temperature change of each probe against time. The Indoor probe required 2160 seconds to raise the temperature by 1 °C while the outdoor probe required 640 seconds to raise the temperature by 1 °C. This demonstrates that the indoor probe took triple the time to increase the surface temperature by 1 °C. Therefore, the infill geometry of the 3D

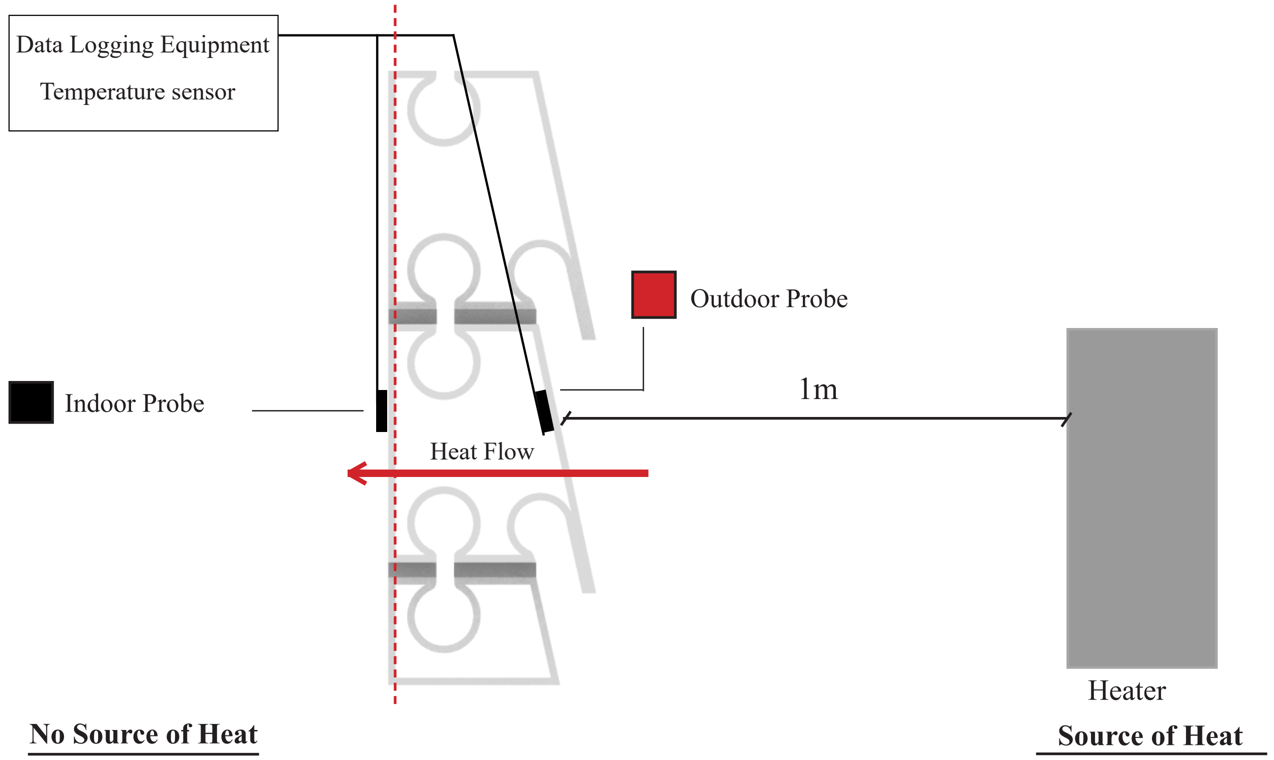


Figure 3.5.2 | Diagram of the physical experiment that shows the placement of the temperature probes.

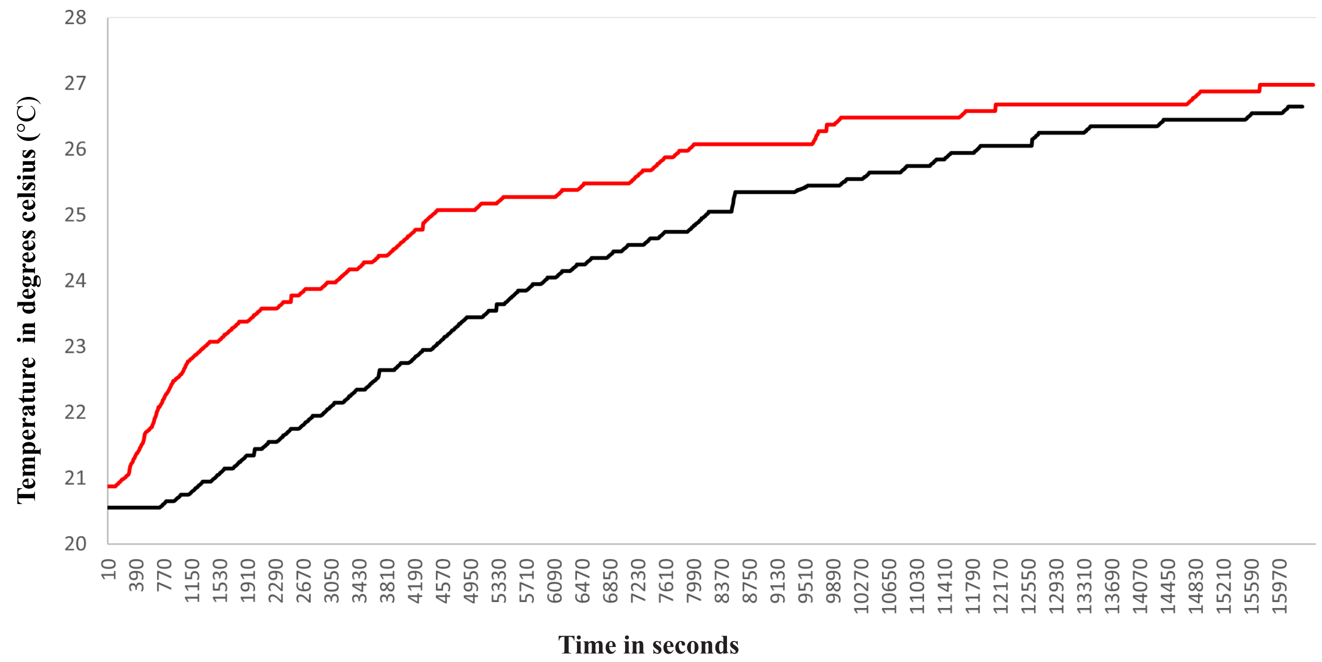


Figure 3.5.3 | The graph illustrates the temperature change of each experiment versus time.

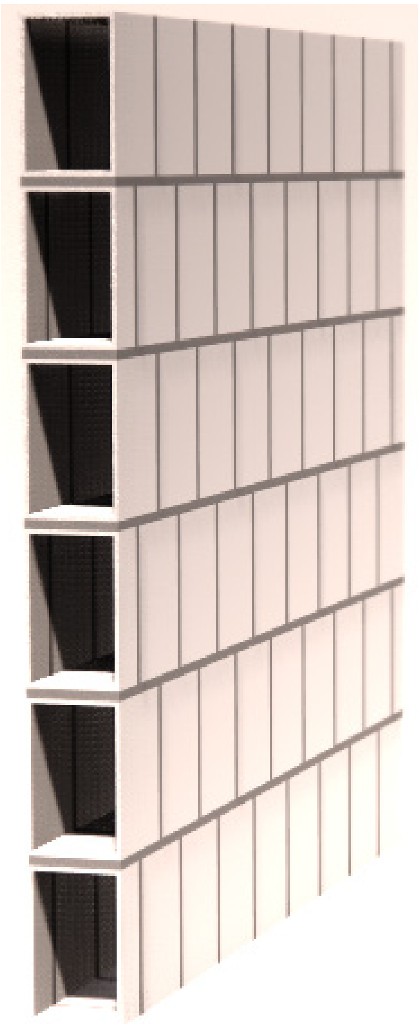
printed brick improves the thermal performance of the design and insulates the interior space more efficiently. Graph in Figure 3.5.3 also demonstrates the time each of the probes takes to reach the same temperature of 25 °C. The Indoor probe required 8160 seconds while the outdoor probe required 4430 seconds to reach to the same temperature. Therefore, the results show that the indoor probe took double the time to reach the same temperature as the outdoor probe. Hence, the geometry of the infill improves the thermal properties of the 3D printed bricks.

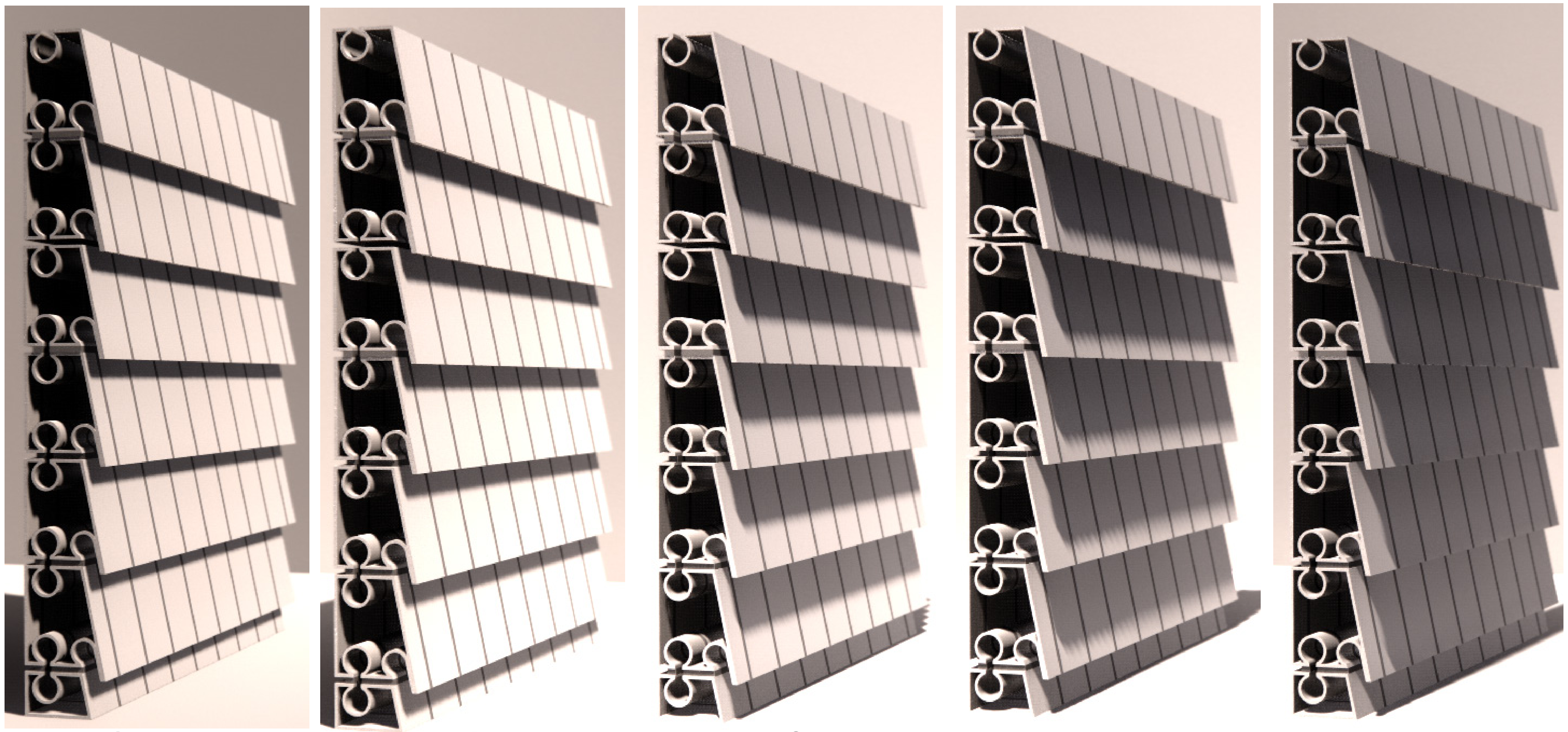
3.6 Shadow and Optimized Rain Screen Development

In addition to the improved thermal properties, the wall system provides shade and functions as an optimized rainscreen. For instance, the traditional clay bricks are exposed to solar radiation for longer periods of time due their rectangular shape, allowing the radiation to be absorbed and converted into thermal energy that accumulates in the walls. Consequently, such bricks allow some of the heat to escape the barrier into the building (Figure 3.6.1). On the other hand, the proposed 3D printed bricks develop into an optimized rain screen wall, which has enhanced thermal properties. The overlapping lip, or the slanted overhang, allows the wall to be shaded for the majority of the day (Figure 3.6.2).

This research investigates the extent of shade provided by the overlapping lip at various times of the day. Moreover, the results will be compared to a traditional brick wall using Enscape software (Figure 3.6.1 and 3.6.2). Figures 3.6.2, 3.6.3, and 3.6.4 demonstrate that the wall provides different variations of shadow patterns as the sun moves across the day. Furthermore, Figures 3.6.3 and 3.6.4 illustrate the shadow variations from sunrise to sunset and at specific times during the day in which one wall faces East and one wall faces West. Figure 3.6.3 demonstrates that, for the wall facing the East, some extent of shadowing is provided throughout the day with the most amount of shadowing provided at 12:00 PM and the least amount of shadowing provided at 6:00 AM. Meanwhile, for the wall facing West, the most amount of shadowing provided before noon and the least amount of shadowing provided at 6:00 PM right before sunset as demonstrated in Figure 3.6.4.

Additionally, compared to the rectangular clay bricks, the overlapping lip or slanted overhang, is more effective and more stable when dealing with rain. In particular, the slope in the bricks' design helps to direct water away from the wall. As a result, the probability of waterlogging is reduced significantly since water cannot rest on the sloped surface for an extended time.

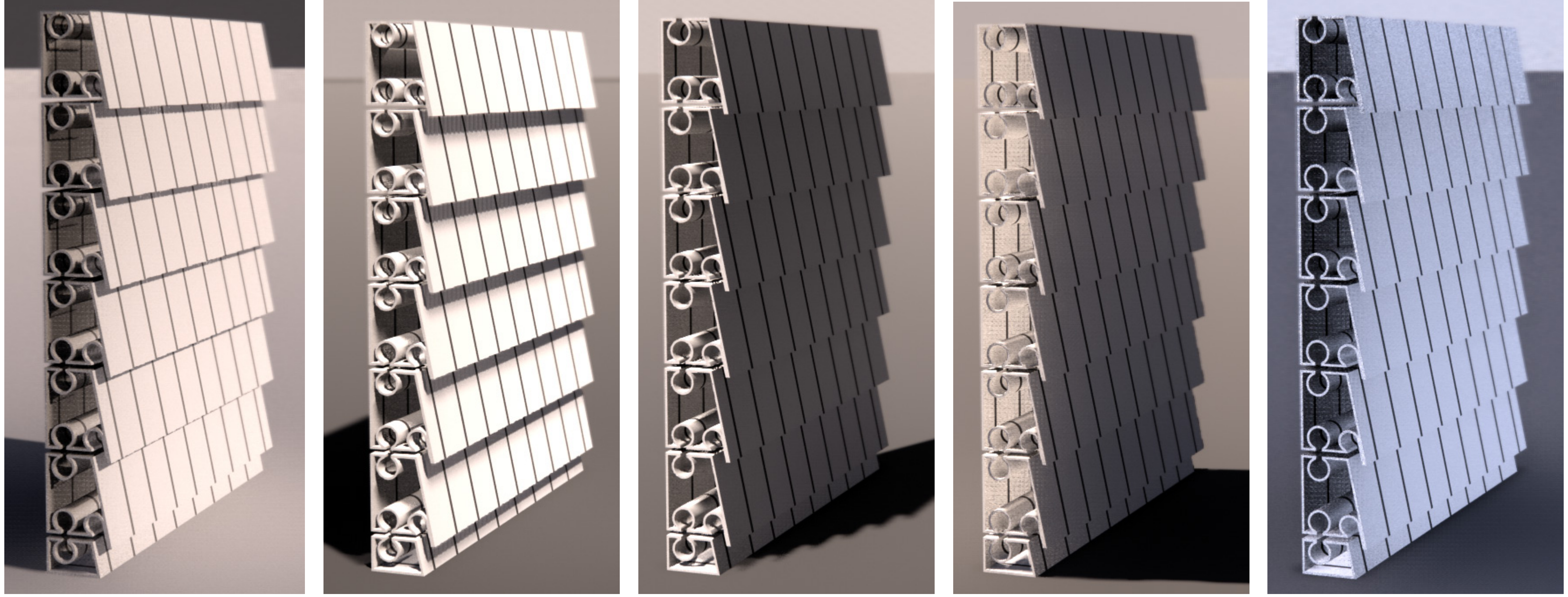




A B C D E

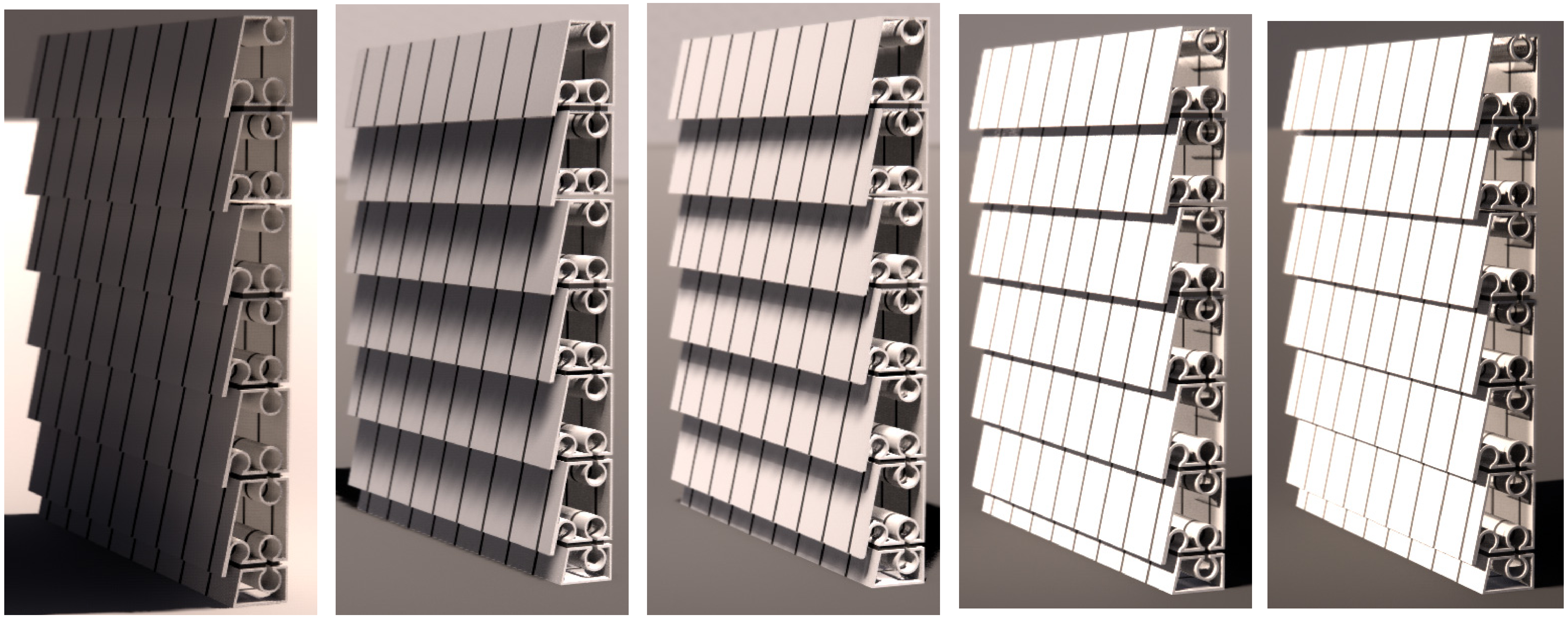
Figure 3.6.1 | Rectangular shaped traditional clay bricks are exposed solar radiation for longer periods of time.

Figure 3.6.2 | 3D printed clay bricks of this research has slanted overhangs that allow the wall to have shaded areas that protects the wall from solar radiation.



After Sunrise AM | 9:00 AM | 12:00 PM | 3:00 PM | sunset PM

Figure 3.6.3 | Wall facing East.



After Sunrise AM | 11:00 AM | 12:00 PM | 3:00 PM | Before sunset PM

Figure 3.6.4 | Wall facing West.

Chapter 4

Discussion

4.1 Discussion

The research initially aimed to use 3D printing tools to investigate the effect of geometry, texture, and air gaps on the brick's thermal conductivity. The research also considered improving the thermal properties of a brick through changing the material properties of clay. In particular, clay bodies can be combined with wood chips to enhance its thermal properties by modifying the material composition and the geometry of clay's inner structure. However, due to time constraints, the thesis focused on manipulating the geometry of a brick to design its thermal conductivity properties without changing the material itself.

Accordingly, the research started by analyzing the geometry of the pre-existing bricks in the construction industry. The construction industry has developed solutions to improve thermal properties of bricks by creating cavities in individual bricks to trap air, as trapped air is a poor conductor of heat. In Germany, Proton Bricks were developed to fill the insulation into the clay bricks instead of adhering it to the outside of the block. However, despite the use of cavities and insulation in the designs, some of these solutions are not designed to be thermally effective because certain heat paths might still function as thermal bridges inside the wall. Additionally, when bricks are stacked, cavities in the brick are filled with mortar. Mortars harden and serve as a thermal bridge via heat conduction (Figure 1.2.1.4.2).

The research also investigated additive manufacturing solutions for improving a wall's thermal properties. Some solutions considered topology optimization, which involved removing excess material volume. As a result, cavities were created within the wall design rather than being solid. However, the wall design was not designed to be thermally effective despite the employment of cavities that existed in the wall design, because there were still certain heat paths that function as thermal bridges inside the wall.

Expanding on the previous knowledge, this thesis conducted preliminary experiments that examined the effect of air cavities on the heat flow by testing various geometry variations in an individual brick. Among the variations were the size of the circular thermal loops, their placement within the brick boundaries, and the frequency with which they occurred within a brick (See Section 3.2). Air cavities were a primary aspect in this research because air trapped inside them is a poor conductor of heat, and therefore, air acts as a barrier to heat transfer. Thermal loops, as secondary elements, helped to maximize the distance that the energy transfer path travels between the interior and exterior of the wall, and thus, reduced heat transfer.

The preliminary experiments were initially designed to include inside and outside air cavities. However, the brick design developed to focus on only the incorporation of inside cavities (inside thermal circular loops). This design development was adopted to maintain the heat path delay effect, described in Section 3.2. In addition, the design of mortar between consecutive bricks was previously placed as a continuous layer between the bricks. However, placing mortar as a continuous layer was unsuccessful because mortar filled in the designed thermal loops. These acted as a thermal bridge and accelerated the rate of heat transfer. As a result, mortar was placed in only the solid parts between consecutive bricks as shown in Figure 3.3.5 and 3.4.1.

The vertical design of the brick provided the opportunity for designing the external design of the brick to an overlapping lip or a slanted overhang, that provides a shaded area (see Figure 3.4.1). This research began to understand how the shading works by conducting shadow analysis in Enscape and comparing the extent of shade provided by the overlapping lip at different times of the day to a traditional clay brick (Figure 3.6.1 and 3.6.2). The results revealed that the overlapping lip allows the wall to be shaded for the majority of the day that provides coolness to the interior by protecting the brick from continuous sun exposure (Figure 3.6.1 and 3.6.2).

Initially, this research considered using a thermal camera scanner to evaluate the thermal effectiveness of the proposed design. However, this was a wrong decision because a thermal camera scanner can only detect temperature variations and the results are used to determine whether insulation is needed and how well it is installed.[99] The thermal camera can only detect energy leaks but cannot measure the thermal effectiveness of a design using numeric values i.e. u-value.[100] The research then investigated how u-value is an effective way to measure the thermal efficiency of a brick design because it is a method of assessing the heat flow or heat loss that occurs through the material due to the difference in indoor and outdoor temperatures.[101] The research used THERM software, a heat-transfer modeling software tool for buildings, to evaluate the energy efficiency of 3D printed clay bricks using the u-value computation and thermal pictures of the design. The software was successful in proving how each of the design steps has a direct impact on the improvement of the thermal properties of the proposed design.

99. “What does thermography do for a building inspection?,” Scan Plus tech, last modified May 23, 2019, https://scanplustech.ca/en/what-does-thermography-do-for-a-building-inspection.
100. “What does thermography do for a building inspection?,” Scan Plus tech,
101. Milad Mahmoodzadeh et al., “Determining overall heat transfer coefficient (U-Value) of wood-framed wall assemblies in Canada using external infrared thermography,”

The research considered measuring the effectiveness of the design through conducting a physical experiment as well. Accordingly, the density of heat flow rate (or heat flux), the difference between the sum of external air temperature and internal air temperature needs to be measured (see Figure 2.5.1.1). However, it was challenging to measure the heat flux of the proposed design using a physical experiment. Therefore, the physical experiment in this research was designed to instead assess the thermal properties of the proposed design as illustrated in Figures 3.4.1 and 3.4.2. The purpose of this experiment was to prove that the geometries developed in the brick's internal structure (or the infill) improved the thermal properties of the brick. The experimental procedure included temperature sensors with a data logger that was successful to collect the temperature change versus time. This experiment was also successful at proving the thermal effectiveness of the design as the results in the graph (Figure 3.4.3) illustrate that indoor probe took triple the time to increase the surface temperature by 1 °C. Therefore, the infill geometry of the 3D printed brick improves the thermal performance of the design and insulates the interior space more efficiently.

The research aimed to prove the thermal effectiveness of the proposed brick as a design by itself (via digital simulations and physical experiment in Section 3.2 and Section 3.4 respectively) as well as in comparison to other existing bricks in the construction field (via the digital simulations in Figures 3.1.1, 3.1.2, 3.1.3). Despite the challenges that the research faced in terms of tool limitations (heat flux measurement tools) or initially selecting a thermal camera scanner as a tool for measurement (which was unsuccessful), the methods used in this research enabled to successfully prove the design's effectiveness. The use of THERM had a significant contribution to this thesis because the software demonstrated that each design step has a direct impact on the improvement of the proposed design's thermal properties.

Chapter 5

Conclusion and Outlook

5.1 Conclusion

This thesis contributed to the construction field by developing a 3D printed brick that is materially optimized, lighter and more thermally efficient in comparison to solid clay bricks. This research achieved a thermally enhanced 3D printed brick without changing the material itself, but rather by manipulating the brick geometry, in terms of both the external shape and the internal geometric structure. The proposed brick was motivated by how solid clay bricks in the construction field are structurally sturdy but are not designed to be thermally effective since their thermal properties are weakened by their homogeneity (Figure 1.1.1). The methods used in this research were primarily digital simulations by THERM software and physical experiment. In particular, 6 digital simulations were conducted using THERM and 1 physical experiment was conducted using a testing apparatus setup with temperature sensors that record the temperature change versus time. The aforementioned tests were conducted to validate the enhanced thermal properties of the proposed brick as shown in Section 3.3 and Section 3.5 respectively. In addition, 8 more digital simulations were conducted to prove the thermal effectiveness of the proposed design in comparison to other existing bricks in the construction field, as explained in detail in Section 3.1, in the research development chapter. In particular, the digital simulations demonstrated that the proposed 3D printed brick has achieved the lowest u-value (a lower u-value indicates an enhanced insulating performance) among all the considered brick designs.

5.2 Outlook

The research demonstrated the possibility of enhancing the thermal properties of a 3D printed brick without changing the material itself, but rather by manipulating the brick geometry. However, the thermal properties of a brick could be further enhanced by investigating other design criteria. This includes enhancing thermal properties of a brick through modifying material properties, through filling the bricks' cavities with insulation and through the design of overhangs and texture. Moreover, since this research is primarily focused on enhancing thermal properties of a brick, further research on structural durability against breakage is an important future research direction.

5.2.1 Enhancing Thermal Properties Through Modifying Material Properties

Clay bodies can be mixed with wood chips to enhance its thermal properties by changing the material composition and the geometry of the inner structure of the material. A study investigated the possibility of incorporating sawdust as an additive material to improve the thermal insulation properties of a clay brick through lowering its thermal conductivity value.[102] According to the findings, the thermal conductivity value decreases with an increase of the percentage of waste (saw dust) added into the clay brick mixture.[103] The use of wooden waste as an additive effectively decreases the thermal conductivity of clay brick.[104] An increase in waste proportion will increase the porosity but decrease the density.[105] The higher the porosity,

102. Rafikullah Deraman et al., "Improving thermal conductivity of fired clay brick using sawdust waste,"
103. Rafikullah Deraman et al., "Improving thermal conductivity,"
104. Rafikullah Deraman et al., "Improving thermal conductivity,"
105. Rafikullah Deraman et al., "Improving thermal conductivity,"

the lower the thermal conductivity value, thus improving the thermal insulation of the materials.[106] Moreover, the decrease of thermal conductivity value creates insulation capability and thermal comfort, while the insulation reduces unwanted heat gain and decreases the thermal conductivity of clay bricks.[107] The thermal conductivity value of clay with sawdust is between 0.4 to 0.6 W/m-K.[108]

The simulations by THERM in this thesis use thermal conductivity value for clay as 1 W/m-K when simulating the 3D printed bricks in THERM software. A thermal conductivity value of 0.5 W/m-K will be used instead for the following simulations to test the effect of using a lower thermal conductive material (clay and wood sawdust) on the u-value of the design. The value of 0.5 W/m-K is based on the study that has been previously discussed. According to the results in THERM software, changing the properties of clay material and mixing it with saw dust has reduced the u-value of the designed 3D printed brick to 2.19 W/m-K (Figure 5.2.1.2). However, the 3D printed brick u-value without changing material properties is 2.35 W/m-K (Figure 5.2.1.1). These simulations illustrate the potential of mixing clay and sawdust as a future research direction that promises further enhancement of thermal properties of a brick.

106. Rafikullah Deraman et al., "Improving thermal conductivity."
107. A., Bahobail et al., "The Mud Additives And Their Effect on Thermal Conductivity of Adobe Bricks,"
108. A., Bahobail et al., "The Mud Additives And Their Effect,"

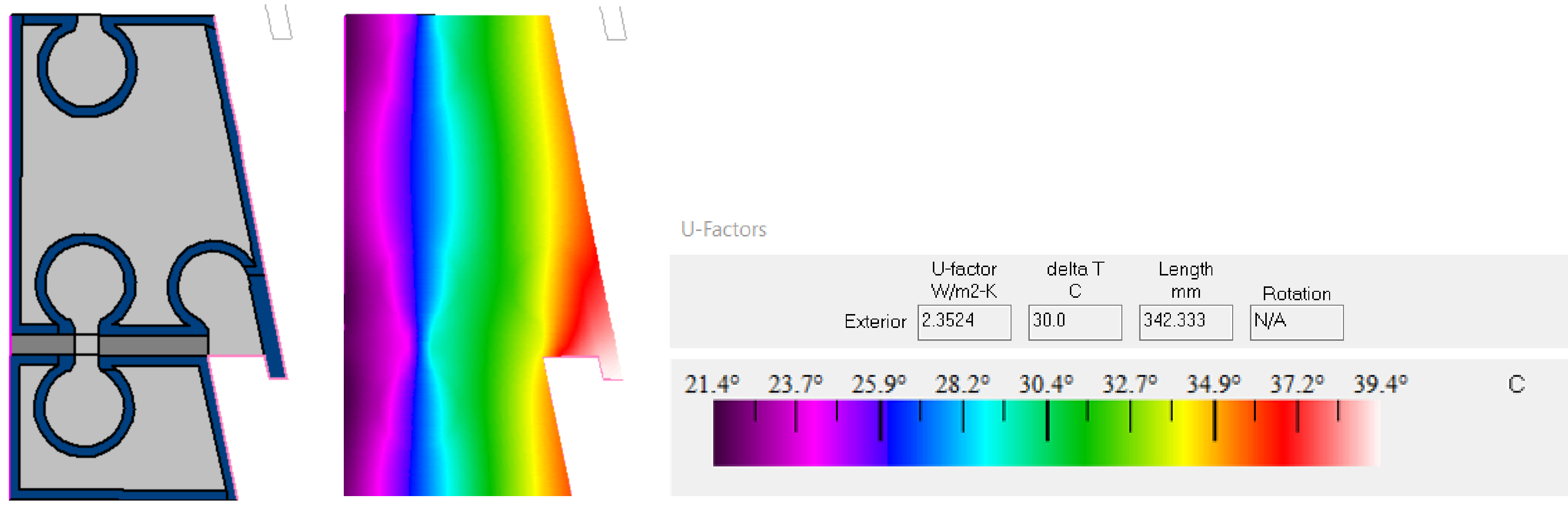


Figure 5.2.1.1 | Step 5 | Design of the proposed brick.

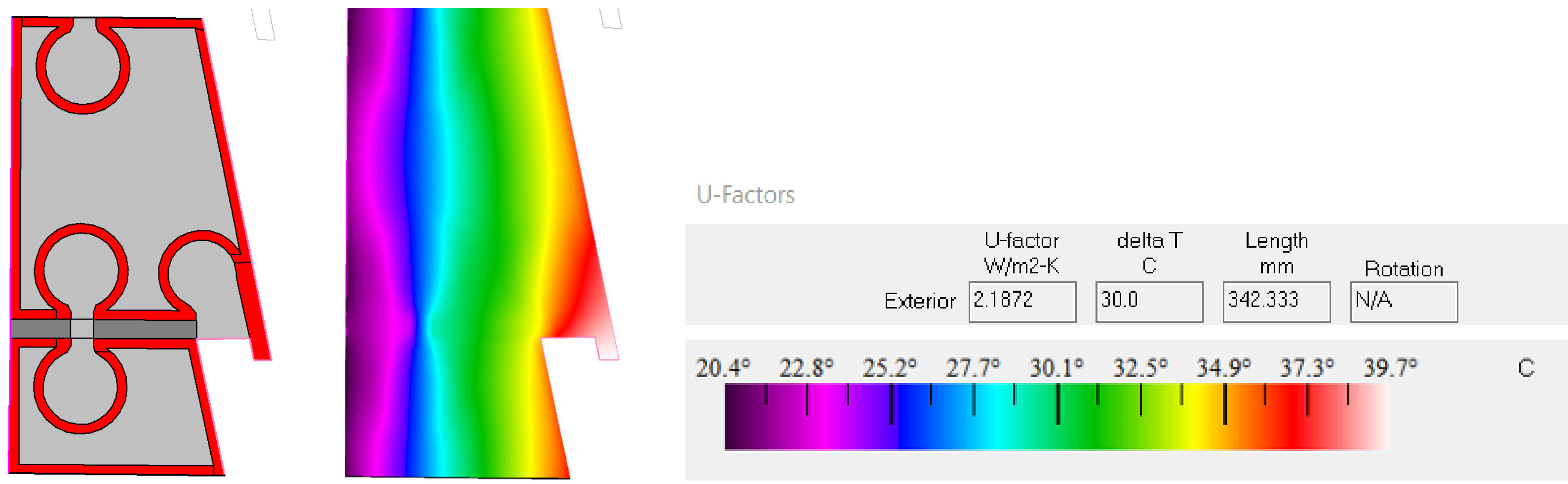


Figure 5.2.1.2 | Step 5 | changing the properties of clay through modifying material properties.

5.2.2 Enhancing Thermal Properties Through Filling the Bricks’ Cavities with Insulation

The proposed 3DP brick can potentially be filled with insulation and thermally tested using a physical experiment similar to the one conducted in the methods section. However, due to time constraints, the thermal effectiveness has only been tested using simulations by THERM software. The results in THERM showed a significant low u-value of 1.00 W/m2-k (Figure 5.2.2.2) when compared the proposed design of 2.35 W/m2-k (Figure 5.2.2.1).

5.2.3 Enhancing Thermal Properties Through Overhangs and Texture

Another design strategy that potentially enhances the thermal insulation characteristics of a wall is the use of textures and overhangs (Figure 5.2.3.1). Previous work has explored how additive manufacturing by extrusion can be used to fabricate building elements that have thermal insulation properties.[109] As long as the material and method allow for the development of overhangs, a deviation of the layer arrangement from one layer to the next is conceivable, resulting in a substantial improvement in geometric flexibility.[110]

109. Klaudius Henke et al., “Additive manufacturing by extrusion of lightweight concrete-strand geometry, nozzle design and layer layout,” 913.
110. Klaudius Henke et al., “Additive manufacturing by extrusion of lightweight concrete-strand geometry, nozzle design and layer layout,” 914.

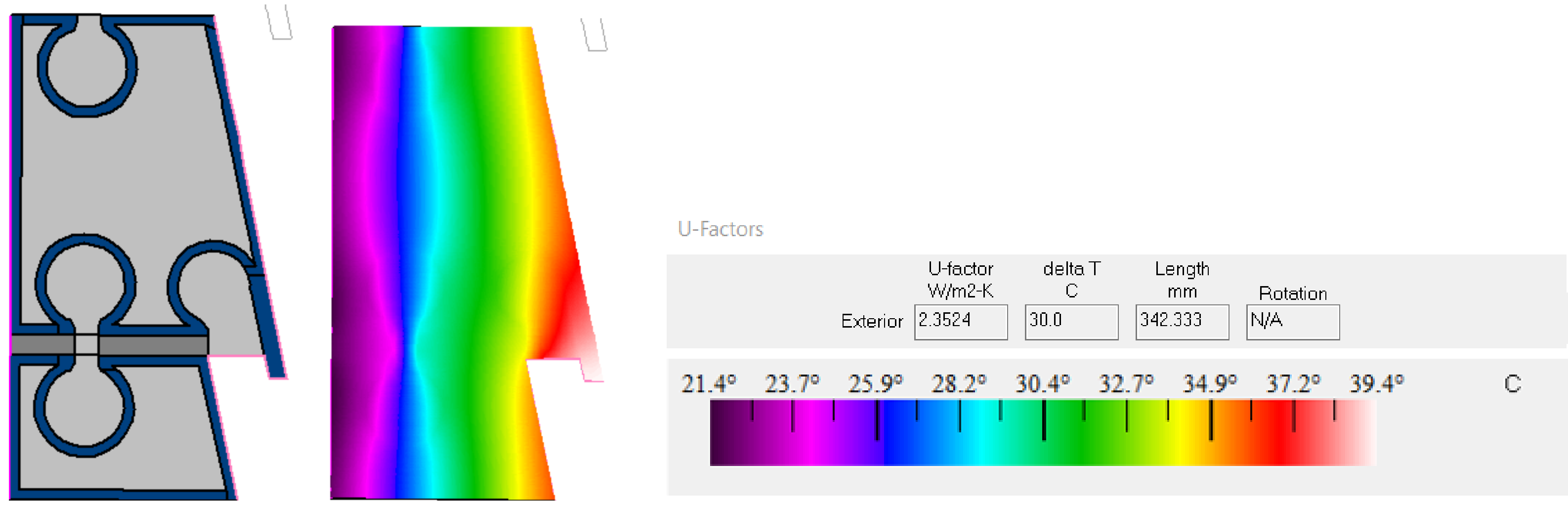


Figure 5.2.2.1 | Step 5 | Design of the proposed brick.

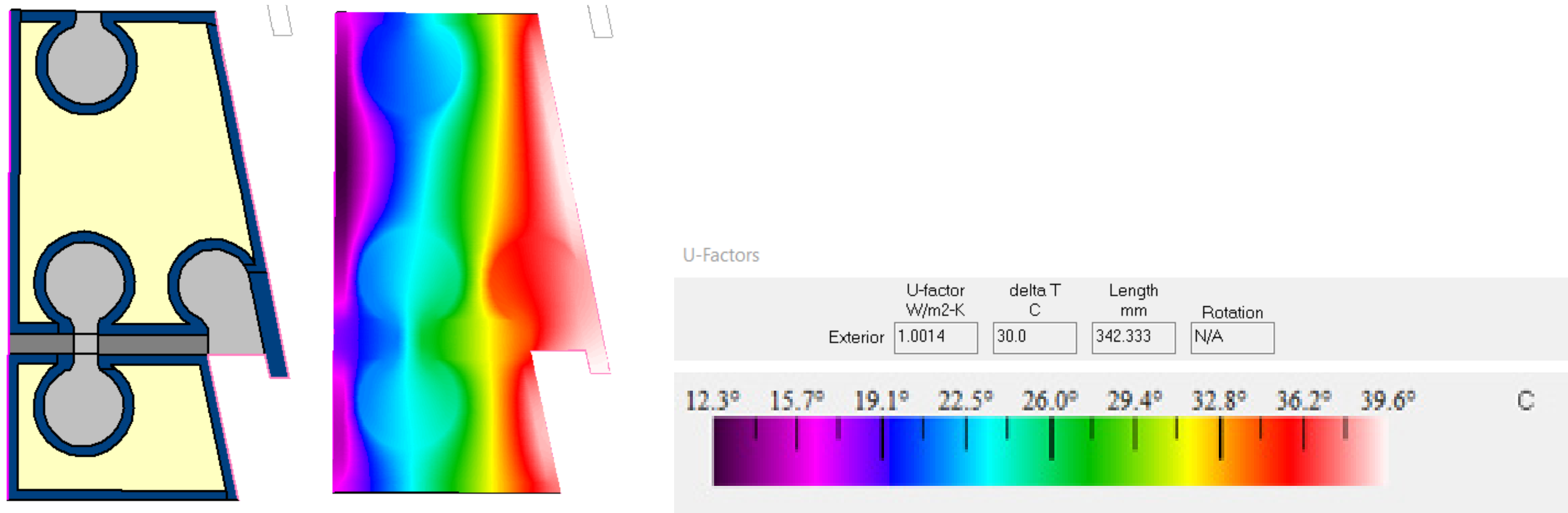


Figure 5.2.2.2 | Step 6 | Introduction of insulation, polyethylene foam, 0.05 W/m2-k.

Thermal properties can also be enhanced through the effects of different panel textures (Figure 5.2.3.2) and air gaps where 3D printed wall panels could enhance the thermal insulation characteristics; reducing the temperature by 4.7 °C when compared to the traditional wall and this resulted in a 50% reduction in the building's energy consumption. In particular, 3D printing minimizes energy usage because of its freeform design that allows for an air gap inside the panel.[111]

111. Lapyote Prasittisopin et al., "Thermal and Sound Insulation of Large-Scale 3D Extrusion Printing Wall Panel." 1175.

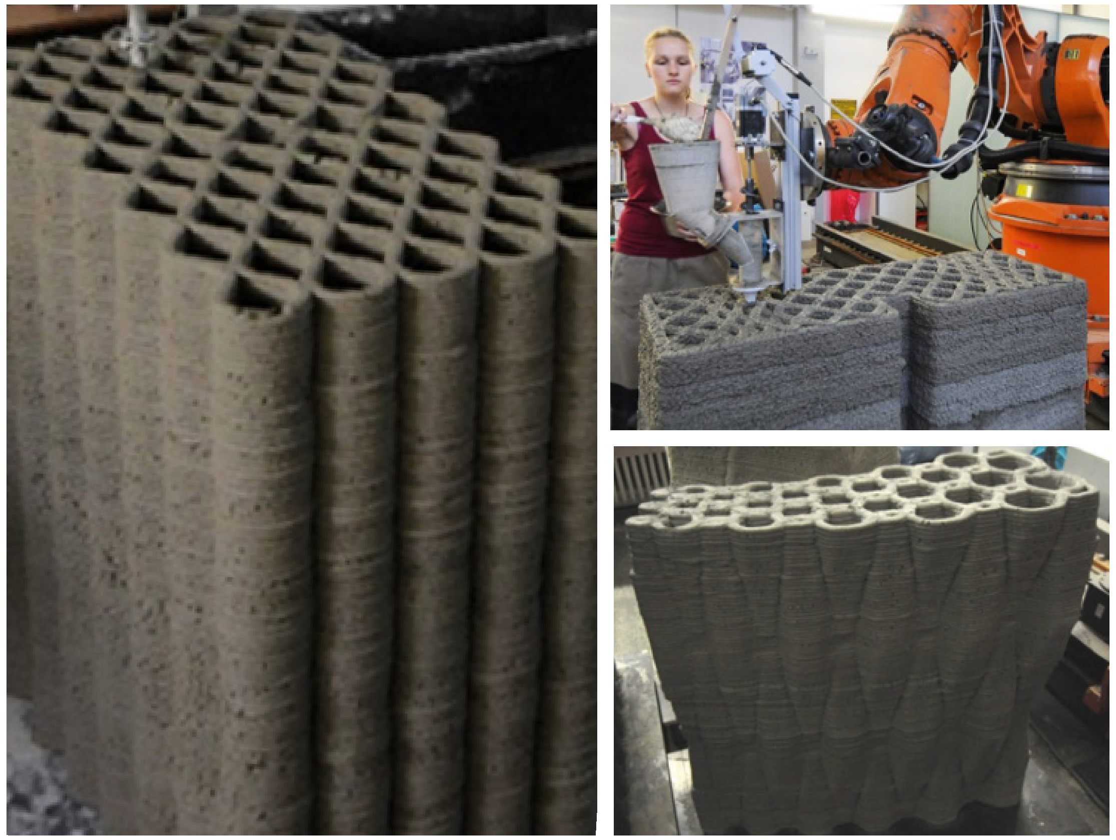


Figure 5.2.3.1 | Enhancing the thermal conductivity through the design of overhangs.

Figure 5.2.3.2 | Enhancing thermal properties through the design of texture, Chanita Chuaysiri.

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