HOW CMU GETS ITS GROOVE BACK

Improving the Thermal Performance of Concrete Masonry Units Through Adaptable Self-Shading

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1. Project Description

1.1. Overview

Energy and aesthetic performance are often at odds in design and construction. Energy performance, commonly led by an instrumental logic, gives little room for a more extensive cultural influence outside efficiency. From its technological inception, Concrete Masonry Units (CMU) have maintained a parallel history of industrial production and aesthetics goals and are conducive to research, such as this proposal, which aims to create a thermally performative material aesthetic. In early concrete block construction, textured blocks mimicking stone or naturalistic motifs were the only few alternatives to flat faced units whose exterior surface matched their construction means. Later, early modern experiments in related block construction, such as Frank Lloyd Wright's textile block works, moved away from the mimicry of earlier construction techniques and naturalistic imagery toward a greater degree of abstract patterning. Patterning, inherent in masonry's bonding logics, developed during modernism to be the defining aesthetic characteristic of CMU. Porous breeze block and highly textured block faces used patterns both within and between concrete masonry units to create rich surface textures that visually explore light and shadow dynamics. CMU in modernist construction forefronted industrial serialization as an aesthetic asset and showcased an early engagement of concrete block construction with environmental performance through ventilation and (shelf)shading. The most recent digital experiments with masonry tend to focus upon the systemic organization of blocks through robotics and CNC technology, techniques that are not economically effective in the majority of market-rate construction.

Figure 1: (L to R); *Allen G. Thurman Home*, 1885; *Ennis House*, Frank Lloyd Wright, 1924; *First Western Bank*, 1956; *Structural Oscillations,* Gramazio & Kohler, ETH Zurich

Today, CMU most often operates aesthetically in the modernist paradigm of serialization or via an early 20th-century mimicry of stone. Neither of these productively addresses the issues related to the built environment's carbon footprint, energy-efficiency in buildings, and computational design, which dominate much of the contemporary architecture and construction discourse.

This research proposal engages such issues using a cross-disciplinary approach that bridges different knowledge fields, including building physics, building performance simulation, optimization, and digital fabrication. The main target is to combine advanced thermal and whole-building energy simulation, optimization, and adaptable construction techniques to develop new thermally improved CMU blocks.

The project engages the surface aesthetic of CMU in an aperiodic and localized manner to improve exterior walls' thermal performance composed of exposed CMU blocks. The investigation examines the benefits of shading the opaque surfaces of building envelopes by embedding grooving patterns that promote CMU blocks' self-shading in building façades. Liu et al. (2019) demonstrated that shading the non-transparent portion of façades reduces building cooling loads and consequently the heat island effect in highly dense urban areas. Despite the promising results of Liu et al. (2019), the study did not perform a comprehensive optimization of different shading profile angles and only considered one location, Hong Kong, where shading is less effective because overcast skies diffuse radiation predominance. Thus, the research team believes there is space to improve and propose solutions whose energy-saving potential goes beyond the literature results, particularly in warm to hot climates dominated by clear skies.

Standard running bond wall assembly organization will be used for simplicity of study and maintain a clear path for future application. The research will focus on optimizing CMU blocks' heat rejection potential through small scale self-shading grooves cast into the CMU face and within assembly logics common to masonry construction. The design procedure combines algorithmic/parametric modeling tools, advanced whole-building energy simulation software, with evolutionary optimization algorithms into a single performance-based generative design system (PGDS) (Santos, 2020). The parametric/algorithmic modeling tools allow the generation of different shading groove patterns. The building energy simulation software estimates their thermal behavior. Finally, the optimization algorithm automatically searches for pattern designs that minimize building cooling loads. This sophisticated approach allows designers to understand better the impact of different shading strategies on the complex transient heat transfer phenomenon that depends on the interplay between thermal resistance, storage, and solar heat gain.

The research then discusses inexpensive fabrication methods to physically test, calibrate, and validate the optimization of the shading groove patterns. The research team proposes developing an inexpensive fabrication method of embedding different form liners into CMU blocks. Such fabrication methods should be easily transferable to industrial production scales and handle the deployment of different block patterns designed for thermal optimization across buildings of multiple scales.

1.2. Research intention and goals

Concrete Masonry Units (CMU) are commonly used in the construction of low- and mid-rise buildings in a variety of climates. This research project aims to investigate the performative potential of using CMU blocks in façades. The overall goal is to develop new fabrication techniques that improve the thermal performance of CMU and their aesthetic quality by proposing surface treatments based on form liner patterns that promote self-shading within the opaque exterior surface of CMU blocks.

Considering that radiation and light-relating phenomena are not affected by proportionally scaling fenestration systems (Choi et al., 2017; Wright et al., 2009), designing and optimizing form liner patterns in façades composed of CMU blocks can reduce cooling loads, and therefore contribute to energy efficiency in buildings. We are also interested in studying the dynamic relationship of CMU’s thermal resistance and storage capabilities in shaping the needs for shading of opaque surfaces. Thus, the authors propose to test the following hypothesis in the course of this research project.

Hypothesis 1

Texturizing a CMU block to promote self-shading is an effective cooling strategy for buildings located in hot climates, particularly in dense urban areas affected by the heat island effect. Embedding shading in a thermally broken CMU block might also yield cooling energy savings in buildings located in mild temperate climates and climates with cold winters and warm summers.

Hypothesis 2

It is possible to embed different shading patterns into CMU blocks using form liners within the block form. Utilizing Computer-Aided Manufacturing processes might improve current CMU blocks' thermal performance with little modification of standard industrial fabrication techniques.

Hypothesis 3

Embedding different shading patterns in CMU blocks improves their ability to handle different solar heat gains loads while augmenting their aesthetic potential in building envelopes with different solar exposures.

1.3. Hypothesis Testing

The test of these hypothesis requires answering the following research questions:

1. Is the self-shading of the opaque surface of façades composed by CMU blocks effective? If so, in which conditions shelf-shading is more effective (i.e., which climate types, and urban situations)?
2. How to optimize the shading of CMU blocks in different climates and solar exposures?
3. What is the less disruptive fabrication method that embeds different form liners patterns in current CMU production flows?
4. How to optimally combine different form liners patterns in complex building envelopes with variable solar exposures?
5. What are the architectural compositional qualities of different assemblies of applying the resulting CMU units?

Questions 1 and 2 directly address hypothesis 1. They aim to investigate the impact of embedding macroscopic shelf-shading properties in CMU elements in overall building thermal and energy performance. Question 3 targets hypothesis 2 by inquiring about the feasibility of adapting current production CMU techniques to incorporate varied form-liner patterns as the main mechanisms through which self-shading will occur. Questions 4 and 5 address hypothesis 3. Question 4 inquiries about a method that allows designers to optimally arrange different shading patterns using a discrete construction element to reduce building energy consumption. Question 5 examines how flexible and expressive is the proposed system in allowing architects to express different building surface patterns using an assembly approach based on unitized elements. Answering question 5 also positions this research in the larger context of digital architecture, particularly in adding a performance dimension to ornament's function and utility. The proposal goes beyond the notion outlined by Moussavi and Kubo (2006) that ornament is a cultural mechanism that organizes architectural material and expresses “unique affects.” Additionally, it inquires about the performative potential of using a serialized construction product to shape dynamic complex façade patterns caused by the everchanging graphic game of light and shadow. This graphical exploration will discuss two opposite approaches; one that emphasizes the discreteness of the system, by exploring what Giles Retsin defined as discretism (Retsin, 2019), the other that explores stepwise façade rationalization to achieve seamless transitions in continuous variable façade patterns (Caetano and Leitão, 2018). The following section describes in more detail the tasks used in testing the hypotheses.

1.4. Research Plan

The testing of the research hypothesis encompasses the following activities, each one with specific tasks.

Preliminary Design

Here the investigation first will be framed in terms of disciplinary and methodological approach scope. The research team will then assess the benefits of adding self-shading of CMU blocks to reduce cooling loads in buildings and propose an initial set of optimized shading grooving patterns to be further tested. Three main tasks compose the initial research effort as follows:

- **Task 1 - Literature review**
  This task aims to thoroughly map the state-of-the-art of the different disciplinary fields that concur and support this research, including generative and parametric design, building energy simulation, digital fabrication, construction methods, and building physics. Special emphasis will be given to Building Performance Optimization (BPO) design processes supported by thermal and whole-building energy simulations, simulation calibration and validation, experimental testing of building elements' thermal properties, and fabrication methods.

- **Task 2 - Assessing the impact of adding shading into CMU blocks**
  In this task, the research team will use computer simulation to estimate the impact of providing shading to façades composed of CMU blocks. The goal is to map which climates and facade orientations the shading of the opaque envelope effectively contributes to reducing cooling loads in buildings. The team will conduct a thorough sensitivity analysis using a brute force simulation approach (Bernstein, 2005) where all combinations of different shading profile angles and types (i.e., horizontal and vertical shades) for each cardinal direction will be simulated using EnergyPlus (Crawley et al., 2001), a state-of-the-art building energy simulation tool. The team envisions performing this sensitivity analysis for each of the 19 ASHRAE (American Society of Heating, Refrigerating and Air-condition Engineers) climate zone subtypes in the United States. The purpose is to determine the climates where shading of the opaque surface is useful. Because this sensitivity analysis involves a large combinatorial number of simulations, the team will use the Ohio SuperComputer resources to expedite this task.

  The results of the sensitivity analysis will determine which are the relevant parameters in shading opaque surfaces that have thermal mass properties.

- **Task 3 - Preliminary Optimization of CMU Assembly**
  Here the team aims to study solar shading groove patterns in a standard running bond block wall assembly. A feedback loop of thermal performance testing and graphic capacity will be tested virtually to develop a block pattern suite system with both aesthetic and improved thermal performance. Using the sensitivity analysis results performed in the previous task, the research team will conduct an optimization experiment that aims to determine the shading groove patterns that minimize cooling building loads in selected climates. The selection criteria for these climates consist of identifying the locations where shading the opaque surfaces of buildings effectively reduced thermal loads in buildings.

  This experiment will require the development of a performance-based generative design system (PGDS) that combines a parametric model, EnergyPlus as the building energy simulation engine and an optimization metaheuristics (e.g., Genetic Algorithm, Particle Swarm Optimization). The parametric model will generate different shading groove pattern designs. EnergyPlus will be the analysis module of the system and evaluate the designs according to their thermal performance. Based on the simulation results, the metaheuristic will search for the pattern that yields minimal cooling loads. The inverse-design process of the proposed PGDS will be applied in various Department of Energy (DoE) reference *Building Energy Models (Department of Energy, 2021)*, particularly the small and medium offices, warehouse, mid rise apartment, and small hotel building types.

From the solutions found by the proposed PGDS, the authors will select different designs per orientation for prototyping and physical testing. The selection criteria will consider the difference between the improved groove patterns found for the same orientations in the various selected climates. In other words, the authors will prioritize significantly different patterns found for a specific solar exposure in different locations.

The research outcomes of this task will be directly used in the following research activities. The preliminary optimization results will be used in the prototyping activity to calibrate and further refine the optimization process proposed in this task. The authors also envisioned to use the developed digital workflow for designing, simulating, and optimizing shading groove patterns in façades composed by CMU blocks in the application to design research activity.

Fabrication and Physical Measurement of the Thermal Properties of CMU Prototypes

This activity focuses on developing a fabrication process that effectively imprints shading grooving patterns in current CMU block production processes. The authors understand that an effective fabrication process of self-shading CMU blocks is the one that achieves the purpose and minimizes disruptions in the current industrial fabrication process. We believe that this is a critical milestone to achieve since it would determine a faster adoption of this technology by the industry at a minimal cost. The authors will test and incrementally improve the proposed fabrication process by assembling a set of CMU blocks selected in task 3 of the Preliminary Design activity.

This research activity also aims to determine prototypes' thermal properties, particularly their thermal resistance (R-value). Other thermal properties such as thermal storage will be calculated by using standard and validated procedures (ASHRAE, 2017, 2013). Such calculations require weighing the blocks, measuring their volume, and using reported values for density and heat capacity for CMU blocks (ACI Committee 122, 2010; International Code Council, 2006).

The R-value of a construction material impacts conductive heat transfer. The transient interplay of thermal resistance, storage, and shading needs to be carefully studied, particularly in temperate climates that benefit both from passive heating and cooling high thermal mass (e.g., ASHRAE Climate Zone 3). Thus, it is important to determine the real R-value of the proposed CMU assemblies and compare it with the R-value assumed in the thermal simulations. The preliminary optimization process supports the initial simulation values, and the testing will assess if the R-value differences introduce relevant changes in the optimization process.

This research activity encompasses the following tasks to achieve its envisioned purpose.

- **Task 4- Form Fabrication and Form Liner Milling**
  Reusable rubber form liners will be tested in this task for their viability in forming custom patterned CMU blocks based upon the digital simulation and optimization testing conducted in Preliminary Design. The various patterns' precise dimensions will be milled from solid surface positives molds for the flexible rubber form liner used in the casting process. The form lines' volume will be accommodated in customized block molds created to maintain the industry standard dimensions of commonly available load-bearing CMU. 8" CMU Full Block has nominal dimensions of 8" x8" x16", and actual dimensions of 7 ⅝" x7 ⅝" x15 ⅝". See Figure 2 for block form and form liner assembly.

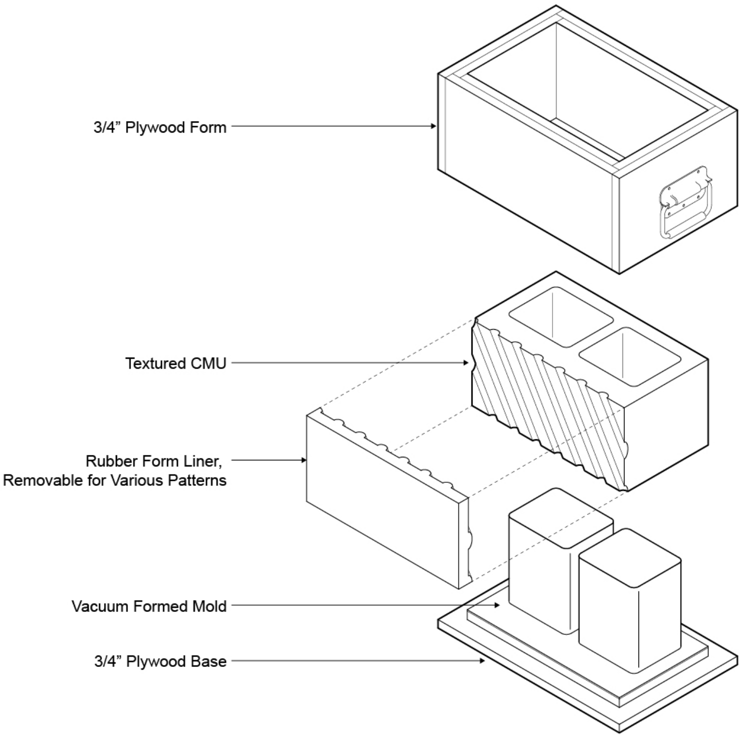

Figure 2: Exploded axonometric view of envisioned CMU block and replaceable form liner assembly.

- **Task 5 - Block Forming and Fabrication**
  This task will test block fabrication techniques and material capacity of CMU to form the groove patterns developed during phase 1. This material based fabrication will create a series of small wall swatches to use in physical testing of thermal performance of the different assemblies. A common CMU concrete mixture is outlined below.

  Material Composition:
  Mixture design guidelines for CMU from GCP Applied Technologies (Jablonski, 1996)
  46% Fine Aggregate
  54% Coarse Aggregate
  1:10 Cement-to-aggregate ratio
  5% of Total Batch Weight Water (Water content of Sand and Gravel + Added Water)

  During the fabrication of the blocks the researchers will develop a log of potential improvements to be introduced in the final design unit fabrication.

- **Task 6 - Wall Assembly and Testing**
  Small wall swatches will be built in this task for physical testing of self-shading efficacy and the impact of self-shading on r-value. Seven of each custom patterned derived from the digital simulation will be fabricated during Task 5. Wall swatches, which are 2'x3', will be assembled from the custom fabricated blocks. This test aims to verify and inform assumptions and findings from the digital simulation of various patterns impact on wall performance.

  Following the guidelines provided by Peters et al. (2017) the research team will build a guarded hot box to study the wall assembly's thermal resistance that uses the improved CMU blocks developed in the Preliminary Design activity. The guarded hot box's calibration will follow the instructions provided by Asdrubali and Baldinelli (2011). The determination of the U-factor (BTU/°F·ft2·h) and R-value

(°F·ft2·h/BTU) of the CMU assembly will follow the protocol described in the American Society for Testing Materials (ASTM) C1363-11 and C177013 standards (ASTM, 2014, 2013).

Final Unit Designs

This research activity focuses on refining the design and fabrication of the CMU blocks tested in Task 3 (Preliminary Design) and validating the simulation-based optimization process used to develop the shading grooving pattern. Using the physical measurements collected in Task 6, the research team will calibrate the simulation-based inverse design process to validate its results. This calibration assesses whether using accurate measurements to thermally describe CMU blocks result in grooving patterns that differ, either in orientation or in shading profile angles, from those found in the preliminary design. Finally, based on the prototyping process, the research team plans to introduce adjustments to improve the proposed fabrication process. In sum, this research activity entails the tasks described as follows.

- **Task 7 - Calibration of the simulation-based optimization process**
  This task is three-folded. First, the research team will compare the CMU blocks' thermal properties in Task 3 with the physical measurements conducted in Task 6 and calibrate the thermal simulations used in the shading groove patterning optimization. Second, the optimization experiment is repeated using the calibrated simulations. Finally, the research team will compare the results of this refined optimization with those previously produced in Task 3 and select the unit design to be fabricated.

- **Task 8 - Fabrication of the final unit designs**
  This task consists of refining the fabrication and assembly process of the self-shaded CMU blocks based on the prototyping process proposed in Tasks 4 and 5. The final assembly of CMU blocks consists of the units selected in Task 7.

Application/Dissemination

This primary research activity aims to assess the potential of applying surface graphical and performance treatments to CMU blocks in the context of architectural design and disseminate the results of the research both to the design, industrial, and scientific communities. The activity entails the following tasks.

- **Task 9 - Studio Fall 2021**
  Parallel and complementary to the technical research, a design studio course in the Fall of 2021 would study how the custom self-shading CMU block can affect other integrated building design aspects. The course will incorporate environmental simulation and performative exterior graphic patterning for thermal performance within a larger formal and architectural design studio. Digital tools developed during the early parts of the grant will be packaged and provided to the students for their design exploration. Each student will be taught simulation software, create a building form that utilizes thermal analysis for a given environment, and then deploy the suite of self-shading block typologies developed in earlier grant research to optimize their design further. Exterior graphic patterns derived from the self-shading CMU blocks place aesthetic performance and thermal performance into dialogue, situating a core group of students to participate actively in the research application of an integrated material construction system.

- **Task 10 - Exhibition**
  Projects developed by the students would be developed into an exhibit with the larger body of research production. The student’s design proposals, physical models, highly detailed drawings, and digital simulation work will be displayed beside, atop, and in conjunction with the large array of custom CMU blocks built and tested. Blocks initially used for thermal testing would be repurposed as pedestals and displayed as full-scale material swatches of the student design proposals. Display in the CAED will be sought first, and galleries of similar scale, such as the RISD Architecture, Pink Comma, or Materials and Application galleries, will be pursued for further exhibition.

- **Task 11 - Scientific Dissemination**
  The research's multidisciplinary nature allows delivering and disseminating results in relevant areas related to architecture and the built environment, including building science, simulation, and digital design. The P.I.s of this research project aim to publish and disseminate the investigation results in first quartile (Q1) scientific peer-review journals and conferences. A detailed list of potential Q1 conferences and journals can be found below in the Impact Statement section. Finally, the research activities and results will be summarized in a publicly-available technical report.

1.5. Research Activities Schedule

Figure 3 presents a gantt chart of the envisioned schedule for the different research activities and correspondent tasks, assuming that the research grant period starts early May 2021 and ends May 2022

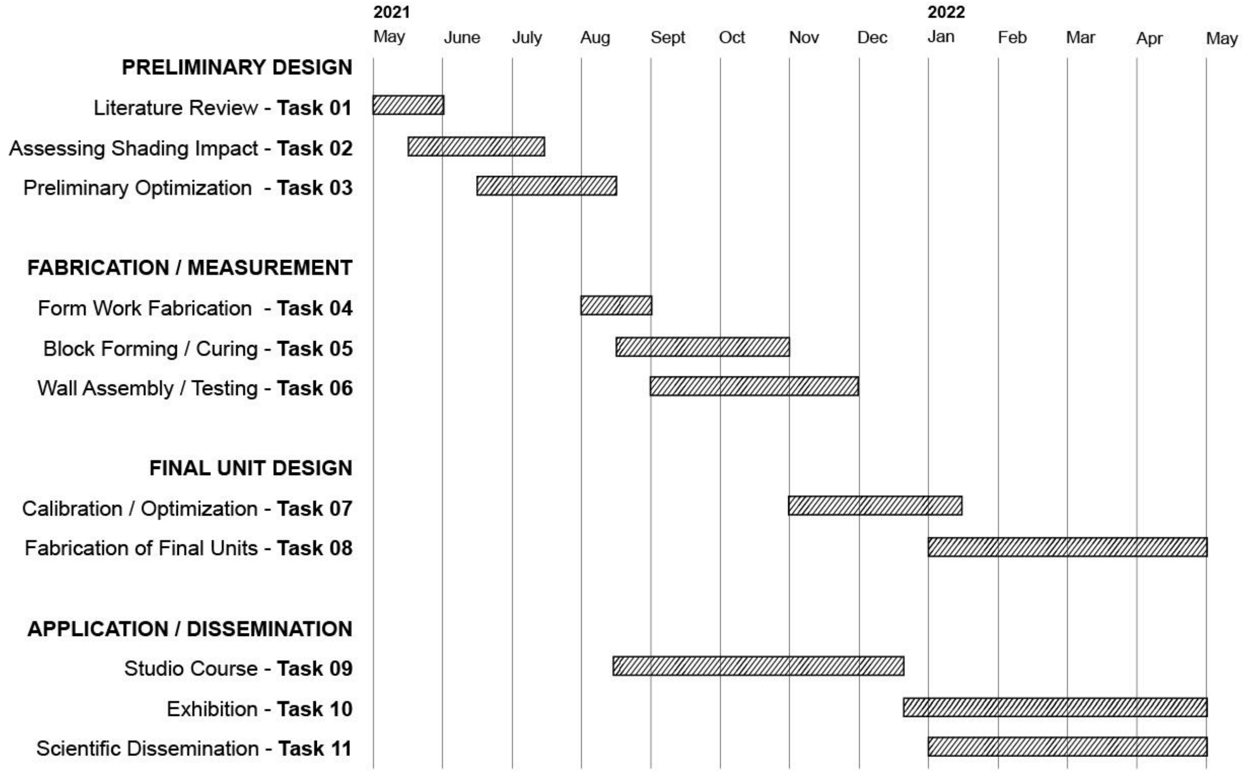

Figure 3: Gantt chart of the planned research activities.

1.6. Project Budget

The table below describes in detail the budget planned for conducting the proposed research.

GENERAL TOOLS	#	UNIT	COST	TOTAL COST	NOTES
Concrete Trowel	2	-	20.00	40.00	
Shovel	1	-	20.00	20.00	
5 Mil Plastic Sheeting	2	Roll	25.00	50.00	
5 Gallon Bucket	5	-	4.00	20.00	
Wheelbarrow	1	-	110.00	110.00	Concrete mixing
Drill Grout Mixer	1	Bag	15.00	15.00	For Grout Mixing
Digital Scale	1	-	150.00	150.00	400 lb capacity Uline
CONCRETE BLOCK MATERIALS	#	UNIT	COST	TOTAL COST	NOTES
Portland Cement (94 lb bag)	12	Bag	13.50	162.00	2 Physical Tests: 60 - 90 Blocks per Test
Sand (50 lb bag)	12	Bag	4.00	48.00	Small Aggregate
Limestone Gravel (40 lb bag)	12	Bag		12.00	Large Aggregate

Bags Mortar (60 lb bag)	5	Bag	5.10	25.50	Setting Test Walls
CMU FORMS	#	UNIT	COST	TOTAL COST	NOTES
3/4" Plywood (4'x8')	2	Sheet	53.00	106.00	8”x8”x16” Sized to match standard block
1/8" Vinyl Sheet	5	Sheet	27.00	135.00	Vacuum Formed Interior Void Mold Interior
Latex Exterior Paint	1	Gallon	15.00	15.00	For plywood for waterproofness
Polytek 75-65 Liquid 2 Part Room Temp Rubber Mold	2	Bottles	140.00	280.00	Flexible rubber form liner cast at custom angles for shading grooves.
CNC Machine Time	10	Hours	20.00	200.00	CAED Shop Rate
1 1/4" Wood Screws	1	Box	8.00	8.00	1 1/4" Wood Screws
1/2" Solid Surface (30”’x72”)	4	Sheet	172.00	688.00	Positives for casting grooves into formliner
THERMAL TESTING HOT BOX	#	UNIT	COST	TOTAL COST	NOTES
2” Thick Rigid Insulation (4’x8’)	6	Sheet	34.00	204.00	Expanded Polystyrene
3/4" Plywood (4'x8')	2	Sheet	53.00	106.00	Box Exterior
Aluminum Foil	1	Roll	30.00	30.00	Heat Reflector
Aluminum Foil Tape	1	Roll	8.00	8.00	To seal reflector
Silicon Caulking	2	Tube	6.70	13.40	Clear
Rolling Casters	4	-	13.10	52.40	McMaster Carr
Door Hinges	2	-	11.00	22.00	McMaster Carr
Wood Screws	1	Box	8.00	8.00	1 1/4" Wood Screws
Temperature Data Loggers (HOBO)	4	-	180.00	720.00	OnSetCom
Power Resistors (for heaters)	1	Box	10.00	10.00	Amazon * per box
Heat Flux Meter	2	Sensor	300.00	600.00	Fluzteq Large Pad. One for hot and cold side
Data log for Heat Flux	1	-	600.00	600.00	Flexteq
PC Cooling Unit	2	-	135.00	270.00	Packaged unit to regulate hotbox temperature.
Arduino circuit board	1	-	25.00	25.00	To regulate the box temperature
RESEARCH / STUDENT EXHIBIT	#	UNIT	COST	TOTAL COST	NOTES
Large Format Printing Student Drawings	-	-	-	1000.00	
Large Format Printing Research Graphics	-	-	-	850.00	
Printing Small Research Booklet	-	-	-	396.70	
STUDENT EMPLOYEES					
Student Employee 1	250	hours	13.00	3250.00	$13 / hour CAED rate
Student Employee 2	250	hours	13.00	3250.00	$13 / hour CAED rate
MATERIAL CONTINGENCY				1500.00	10% of Total Budget
TOTAL BUDGET				$15,000.00	

2. Impact Statement

The multidisciplinary nature of the proposed research plan imparts the following types of impacts.

2.1. Industry impacts

This research can positively impact the CMU industry by improving and extending current fabrication CMU processes, enhancing the thermal capabilities of CMU products, particularly in terms of heat rejection, and revitalizing the aesthetic potential of CMU blocks in stereotomic-based architectural design approaches. The proposed integrated study of both thermal performance and CMU graphic qualities in façade composition could improve the marketing potential of CMU products, particularly among architects interested in energy-efficient building design. In sum, the proposed investigation has the potential to generate the following patents.

- *Removable Form Liner Process*: this patent will adapt the small batch process used in research to large scale industrial production of CMU blocks.

- *Specific High-Performing Shading Groove Patterns for CMU Blocks*: this patent will describe standardized patterns of equivalent shading performance for particular orientations, climates, and geographical location. Additionally, it would also prescribe a process that giving a specific location, and orientation, determines the main geometric features of the grooving patterns that effectively reduces cooling loads due to shading of the opaque portion of building envelopes.

Additionally, the sensitivity and optimization studies proposed in the research plan has the potential to map where the proposed CMU blocks would be more effective and therefore more marketable.

2.2. Design impacts

The proposed research contributes to amplify the applicability and design potential of current construction material. Integrating stereotomic, compositional, and thermal performance aspects allows designers to fully explore ornamental and performance qualities of the CMU material and construction technique. The digital design workflow envisioned in this research will facilitate the exploration of design possibilities and enable a balanced examination of both the potential designs' thermal performance and their emerging aesthetic value. Such a digital workflow will be a powerful design, analysis, and performance-optimization tool. This tool can potentially allow designers to describe shading grooves parametrically, discretize them, and determine the optimal location for different suites of developed patterns.

Additionally, the sensitivity analysis and optimization tasks included in this research can generate guidelines about useful shading profile angles depending on climate, location (i.e., latitude), and solar orientation for shading the opaque portion of building façades.

2.3. Scientific Impacts

This research will positively contribute to a better understanding of the usefulness of shading opaque building surfaces in mitigating heat gain, particularly in dense urban areas susceptible to heat island effects in various climates. As stated by Liu et al. (2019), although it is known that shading the opaque portion of façades contributes to reducing building cooling loads, little research has been conducted to measure its impact fully. This research will extend the work of Liu et al. (2019) by considering a wider range of different locations, climates, and shading patterns.

Additionally, the simulation, physical testing, and calibration of the digital workflow will also provide useful insights on the transient heat transfer phenomena directly affected by thermal resistance, thermal storage, and shading.

This research project will also advance new modeling techniques for whole-building energy simulations of highly-granular shading systems directly embedded in the construction material.

The scientific results produced by this research will be summarized into a publicly available final technical report. They will be disseminated in several scholarly articles to be either published or presented in top-tier (Q1) peer-review scientific journals or conferences. Potential journals include Building and Environment, Energy and Buildings, Automation and Construction, Design Studies, Architecture Science Review, Buildings, Energies, Frontier of Architectural Research, Journal of Architectural Education (JAE), and the Technology|Architecture + Design (TAD). The presentation and publishing in scientific conference proceedings will target the following conferences: (i) Building Simulation, (ii) the Symposium on Simulation in Architecture + Urban Design (SimAUD), (iii) the Association for Computer-Aided Design in Architecture (ACADIA), (iv) Education and research in Computer Aided Architectural Design in Europe (eCAADe), (v) CAAD Futures, (vi) Façade Tectonics, (vii) Facade+, and the (viii) CAADRIA from the Association for Computer-Aided Architectural Design Research in Asia.

3. Facility Needs

This research will require access to the Fabrication Shop Access and a designated research space, preferably in the CAED, for material preparation, fabrication of CMU blocks, assembly of CMU prototypes, and physical measurements.

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