Energy Efficient Design for 3D Printed Earth Architecture

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Abstract. Additive manufacturing with mud has the potential to reintroduce traditional materials within our contemporary design culture, answering the current demands of sustainability, energy efficiency and cost in construction. Building upon previous research, this study proposes the design and test of real-scale wall elements that aim to take advantage of both the novel material fabrication process as well as the significant thermodynamic properties of the material to achieve a performative passive material system for bioclimatic architecture. Although this project is still at an early stage, the presented study demonstrates the potential of combining 3D printing of mud with performance analysis and simulation for the optimization of a wall prototype.

Keywords: 3D printing · Clay · Sustainability · Thermal analysis · Structural analysis · CFD · Optimization · Performance · Simulation

Introduction—3D Printing with Mud

Mud constructions, which are based on ancestral techniques that take advantage of local materials, are today a viable alternative to the contemporary challenges of energy efficiency. Their close to zero ecological footprint is a great advantage in meeting current energy consumption and emission goals. Almost all mineral ground that contains clay can be used for construction. At all stages of its use, clay requires very little embodied energy (e.g. no baking energy and little processing). Its maintenance and repair are easy; it can be recycled and it does not generate waste. Mud constructions allow substantial savings in winter heating and summer cooling thanks to their thermal inertia. Finally, thanks to their ability to absorb and evaporate, clays regulate humidity, promoting a healthy indoor climate. Although mud as a construction material is freely and abundantly available, traditional mud constructions require labor-intensive processes that can’t compete with contemporary materials in terms of cost and quality.

As additive manufacturing (AM) is continuously gaining momentum in the construction industry today, new applications are constantly being discovered. While AM for architecture is yet at an early stage, its clear potential has been identified by industries, contractors and architects. The advancements of CAAD have already led to the design of complex and optimized building geometries and AM is enabling advanced material fabrication and distribution processes, setting the ground for more efficient buildings. AM has the potential to quickly and precisely create these complex...
geometries previously too expensive to make, while permitting a drastic reduction of production waste.

AM with mud has the potential to reintroduce this traditional material within our contemporary culture, answering the current exigencies of quality, cost and efficiency. Although the technology is still in its infancy, examples of additive manufacturing with earth materials, such as clay and mud, already exist in the literature. Friedman et al. (2014) used robotic fabrication and clay deposition to create 3D weaving patterns for table top objects (albeit with no real architectural scale application). Kawiti and Schnabel (2016) also used 3D clay printing but within the context of an indigenous project development and with local materials, closer to the interest of this paper (Fig. 1). The main differences though in our approach are the use of robotic fabrication, aiming at full real-scale 3D printing and our focus on not just the structural but also the environmental performance of clay.

Research Context

The project Pylos developed by Giannakopoulos, has proven the possibility to use additive manufacturing with mud at an architectural scale. For this purpose, the project developed a new material mix, naturally sourced and biodegradable, with a measured strength three times stronger than typical unbaked clay material. A custom extruder mounted on a robotic arm has been also developed along with specific CAD/CAM software that allows the 3D printing of complex geometries (Giannakopoulos 2017). Building upon the potential of this previous project, this study proposes the design and test of real-scale wall elements that aim to take advantage of both the novel material fabrication process as well as the significant thermodynamic properties of the material to achieve a performative passive material system for bioclimatic architecture.

Mud, as a building solution can be useful in any climate. This study has been carried out with an aim to address design solutions for different locations, using local climatic information as a driver for the design of site specific components. The case study presented here has been developed based on the specific climatic conditions of
the context of the Valldaura natural park in the province of Barcelona, where the final full-scale wall prototype is constructed. Local information for solar incidences, temperature and humidity have been used for the simulations and the other design drivers of the wall, to optimize its passive performance capacities. Although the design, analysis and fabrication processes described here are site-specific, the intention of the study is to evaluate the potential of the material and the additive manufacturing techniques to produce performative building components in any climate or site. Since the simulation and performance monitoring methods are not site-specific and the design and fabrication processes are fully customizable, our approach can be replicated for different climates and different performance objectives.

**Simulation and Performance Monitoring**

The overall development of the project presented here involved a thorough research on various aspects of the problem, such as ancestral precedents of earth constructions and their bioclimatic performance, thermodynamic properties of walls and historical use of earthen materials, which despite their significance in the project are not discussed in this paper. This paper, on the other hand, is focusing on the performance evaluation methods used in the project and their impact on the design and fabrication of the prototype wall. To assess and optimize the different aspects of the performance of the wall, i.e. its structural, thermal and ventilation performance in conjunction always with the properties of the material a series of simulation and physical tests were carried out. The diverse and often conflicting performance objectives of the project required a multifaceted performance evaluation, which informed the design and fabrication at different stages. It is not the aim of this paper to provide an exhaustive analysis of each part of the performance assessment of the developed prototype, but rather to give an overview of the process and assess its results at this initial step of the research.

Physical tests and digital simulations have been performed on wall prototypes, using solar radiation, daylight, thermal conductivity, thermal convection, thermal mass and structural behavior analyses. Simulation models were developed in a range of software platforms, such as RhinoCFD, a computational fluid dynamics (CFD) plugin for McNeel Rhinoceros 3D (Rhino), Ladybug and Karamba, two add-ons for the Grasshopper plugin of Rhino to assess the airflow, solar and structural performance of the proposed prototype walls. In parallel, a series of open source performance monitoring machines, such as a hygrothermal monitoring apparatus and a load machine were also developed to validate the design assumptions on physical wall prototypes (Fig. 2). A light visualization exercise was also performed as part of the simulation and design evaluation process by recreating the sun path with the help of an industrial robot. A very important aspect of this study was that the different performance objectives of the wall were constantly assessed in parallel to each other, with each one informing the others throughout the design and development of the project. Due to the complexity of the problem, the performance analysis and monitoring methods used in this study were
not directed towards achieving the greatest possible accuracy but primarily to ade-
quately inform the design and fabrication of the project, enabling the research team to
identify the best compromise for the performance objectives at each iteration of the
project.

Performance Results

Structural Performance

The structural performance of the 3D printed wall was evidently a fundamental aspect
of the project. Although, the performative objectives of the study were mainly focused
towards the thermodynamic properties of the material, the structural stability of the wall
is nevertheless imperative. The structural analysis and optimization was twofold, with
on one hand a focus on the material composition and its consequent structural per-
formance and, on the other, with a focus on the structural optimization of the 3D
printed geometry.

In terms of the material composition, the control of the composition’s parameters,
such as the amount of water, the addition of other ingredients, such as fibers, sand and
proteins were investigated for their significant effect on the material’s viscosity,
shrinkage and brittleness, with consequent effects on its structural rigidity. Issues like
material cracks, elimination of gravitational shrinkage and speeding up of the drying
process were dealt with a meticulous experimentation with the material composition.
The main issue of the material decomposition related to the non-uniform shrinkage of
the material (up to 7%) and the low strength of the uncured clay while printing
(compressive strength <0.2 MPA within the first 6 h of drying). The extensive material
tests and physical prototypes helped define an optimal robotic toolpath and profile for
the 3D printed geometries that maximizes their structural performance.

By comparing the structural resistance under compression of a wide range of
different geometries and topologies, the researchers also identified the most important
design parameters of the wall’s inner and outer parts. Working with a curvilinear
pattern without straight line segments and using a radius larger than 20 mm and pattern
that proved to be more resistant to cracks and overhang fails and had a much better

Fig. 2. Monitoring and performance testing apparati
shrinkage behavior. The continuous periodic decomposition pattern without self-intersections also proved to create stronger bonds between the printing paths while offering a fast and efficient printing process by avoiding the need to stop the extrusion for every intersection. Physical tests using a 3-point flexural strength test were also conducted to assess the structural strength at each stage of the material development process.

Further to a thorough material experimentation, the structural optimization of the modular geometry was also a key aspect of the structural performance of the wall. Digital simulations using Karamba for Grasshopper were done in parallel with physical prototypes and strength tests to find a structurally sound strategy for the 3D printed modules. Issues such as buckling, toolpath joinery and accumulation of vertical load were analyzed in a simplified simulation model, using a uniform material in finite element analysis (FEA). A more thorough structural simulation approach, which would take into account the anisotropic properties of the material over space and time would allow for a more accurate optimization process, but the simplification of the structural analysis undertaken and its seamless integration in the existing design workflow, which was based on the Grasshopper platform, provided valuable feedback to the design process, driving important design decision on the topology and the geometry of the wall. Over a period of 3 months of research, more than 50 different geometry and typology variations of the wall were simulated and evaluated in conjunction with the other performance objectives and a total of 5 different solutions were then physically tested using a load bearing test to validate the performance of the digital simulations. Despite the simplification of the simulation model, our tests verified our initial assumptions and confirmed the informed design decisions taken. The outcome geometry was a conical diagrid structure that was informed by all the aforementioned structural and material issues (Fig. 3).

Fig. 3. Structural performance simulation and physical tests—shrinkage
**Thermal Performance**

The thermodynamic properties of clay have been of the most significant interest in this study. Further to optimizing the thermal inertia of the material itself through experimenting with the material composition, a great effort was also put in using the inner and outer geometry of the wall to receive, store and appropriately dissipate heat. Again, several different topological and geometrical strategies were implemented to assess their different effect on the wall’s performance. The focus on the wall’s infill geometry was towards creating a heat sink, through a modular branching logic that would allow the gradual flux of heat from the outer to the inner part of the wall, to optimize the storage of thermal energy during the day and its dissipation to the inside during the night. The outer surface of the wall’s geometry, on the other hand, was optimized for solar radiation performance during the winter and summer periods. The two strategies combined create a performative wall, whose inner and outer geometries are optimized to receive, store and dissipate internally the heat of the environment, according the specific needs of the site’s climate.

To optimize the outer surface of the wall for solar radiation, simulations were run at all stages of development using Ladybug, an add-on that interfaces Radiance to Grasshopper. At each development stage, the different geometry and topology strategies of the outer surface that were informed by the structural analysis were assessed through solar radiation tests and their geometrical and topological features were used to minimize and maximize the summer and winter radiation, respectively. The final conical diagrid geometry of the outer surface of the wall was informed by these simulations, by finding a compromise for the diagrid’s offset inclination that supports both the structural overhang and the optimum solar incident angle. Using Ladybug for the solar radiation simulations was quite useful, as it was both accurate enough for the purpose of the study as well as integrated in our computational design platform. The solar studies performed allowed us to maximize the total incident radiation by more than 4 times in the winter and minimize it by 70% in the summer. Further to the surface modulation, a comprehensive solar radiation study was also done to optimize the overall geometry of the final wall prototype for the specific site of construction. The final shape of the wall was strategically positioned on the north-south axis to enable greater control of the surface modulation (Fig. 4).

To assess and optimize the thermal performance of the infill of the wall, thermal conduction simulations as well as physical experiments with a custom developed...
apparatus were performed. Initially, heat transfer simulations were done using Energy2D, a visual multi-physics simulation tool, which helped establish basic principles for the infill geometry. However, as the material mix used has not been characterized and thus its heat transfer coefficients are unknown and also due to the overall complexity of accurately simulating the heat transfer of the wall, physical tests were used to measure the performance of different wall modules physically. A custom apparatus of two compartments with a heat lamp was used and the temperature flux was recorded with two sensors. A comparison with a standard wall geometry of the same amount of material showed a significant performance benefit of the optimized infill geometry driving the project to further investigation of its thermal properties. The heat sink geometry strategy demonstrated both a significant temperature drop (10 °C) as well as, most importantly, a significant reduction on the heat transfer time, which is in our case, most useful for the day–night heat cycle objective. Finally, a thermal camera was also used to assess both the solar radiation and self-shading performance of both the inner and outer surfaces of the wall at all stages of the wall development (Figs. 5 and 6).

![Fig. 5. Thermal strategy. Comparison with standard wall (left) and branching strategy (right)](image)

![Fig. 6. Thermal imaging of the wall infill](image)
While the precision of the digital and physical thermal analysis tools used has not always been as accurate as intended, due to both resources and complexity of the project, they nevertheless were proven to be very valuable in the performative design workflow, by giving comparative data between each design iteration and allowing the team to get insight on the performance solution space.

**Ventilation Performance**

Equally important aspect of the environmental performance of the wall has been its ventilation capacity. The ventilation goal was twofold, as it was first and foremost an important environmental driver but also important in the natural drying process of clay. In terms of its environmental performance, the ventilation strategies focused on creating both channeled openings and micro perforations throughout the inner geometry of the wall, which would allow a natural ventilation of the enclosed space. Taking advantage of both the Bernoulli effect but also the inherent thermal properties of the material, airflow channels were designed to drag the air through diminishing openings through the wall and channeling it through the colder parts of the infill to cool the air.

To assess the potential of the inner geometry of the wall in driving and channeling the air, computational fluid dynamics (CFD) simulations were performed on a number of different geometries. The CFD simulations were done to firstly understand the feasibility of the proposed strategy and to analyze the effect of the wall’s geometry on the pressure field of the air on the surface of the wall and identify optimal positions for the openings. The CFD simulations were done using RhinoCFD, a plugin that integrates PHOENICS CFD, an established CFD software with Rhino. The initial studies, despite their simplifications, clearly demonstrated a differentiation effect on the pressure field caused by the different patterns of the external surface of the wall and thus a significant potential for air channeling through the wall. CFD simulations with small openings on the wall also demonstrated strong drafts within the air channels, although these need further work to be validated (Fig. 7). The ventilation studies performed were preliminary and inconclusive at this initial stage of the research, due to the complexity of the given task, and thus the final prototype that was erected on site did not include any openings, as the goal is to first assess the thermal properties of the material itself. However, further work is currently underway to explore the full potential of the wall’s cavities.

**Daylight Performance**

The daylight performance of the wall was also addressed, both through openings as well as again through micro perforations on the external surface of the wall. A strategy of interior light channeling through the wall was taken to minimize the solar gains but keep the light levels high. To assess the daylighting performance of the different strategies, a series of digital simulations were done using Ladybug for Grasshopper, as well as a physical test, using the robotic arm coupled with a dimmable spot light to emulate the different sun positions. The robotic arm test allowed the assessment of the daylight potential not only as a quantifiable metric of luminosity but also from an aesthetic point of view of the ambience of the light created. Generally, although the
daylight studies were an important part of the overall study they are not considered significant for the thermodynamic performance of the wall and there were also not included in the final erected prototype, thus they are outside the scope of this paper.

**Full Scale Wall Prototype**

As a conclusion for this first phase of the research, a prototype of a 2.85 m long, 0.35 m thick wall has been fabricated and assembled at the Valldaura campus of the Institute for Advanced Architecture of Catalonia. It is composed of 55 modules, parametrically designed to optimize the solar radiation, airflow and for structural performance. The wall’s geometry has been conceived as a gradient in both horizontal and vertical directions, with various levels of self-shading to optimize according to the easterly and westerly sun. A number of sensors have also been put in place to measure the thermal performance and the ventilation potential of the wall. This first prototype has been envisioned as an initial stepping stone of this research and further work is currently being done to further investigate the potential of this approach. Nevertheless, this first prototype has been an important driver for research and the study associated with it has drawn important conclusions on the material composition, the geometry optimization and the environmental potential of the approach (Fig. 8).
Conclusions

While this investigation is still on-going, the initial results presented in this paper demonstrate both the potential as well as the inherent limitations of our approach. More specifically, key design limitations, which are dictated by the layered additive manufacturing process of a slow curing material have been identified and used as a driver for further research. Design workflow limitations have also been identified in the currently available simulation tools integrated in computational design software, urging the need to develop new simulation approaches. The issue of resolution and accuracy of the simulation models in adequately informing design decisions for a geometrically complex additive manufacturing process is also in need for further investigation. Furthermore, the potential use of the simulation models for design optimization, which relies on the agility of these models is also an important point.

Such optimization potential lies, for example, on the design of the geometry of the exterior, its heat gain performance on the infill pattern for its thermal conductivity and storage and on the placement of openings for thermal convection and ventilation. Another important aspect of the optimization process proposed is the combination of digital simulation and fast physical prototyping with performance testing of 1:10 wall element prototypes using simple testing apparati and low-cost sensors.

Although this project is still at an early stage, the present study demonstrates the potential of combining 3D printing of mud with performance analysis and simulation for the optimization of a 3D printed wall. The study identifies important pitfalls in the design and performance assessment workflow and serves as a fruitful first step towards
the further development aiming to reintroduce mud as a sustainable material for contemporary digital fabrication techniques.

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