Exploring Extreme 3D Printed Clay Overhangs with Integrated Active Hot Air Drying System on Robotic Arm

Mohamed Abdelaziz[1], Ilija Vukorep[1], Deena El-Mahdy[2]

[1]Faculty of Architecture, Civil Engineering and Urban Planning, BTU Cottbus-Senftenberg, Germany
[2] Faculty of Engineering, The British University in Egypt, Egypt
abdelmoh@b-tu.de, ilija.vukorep@b-tu.de, deena.elmahdy@bue.edu.eg

Abstract –

3D printing has gained significant popularity in construction in recent years, along with a growing focus on earth-based materials. These materials must adhere to certain principles to ensure printability and extrudability, allowing for good consistency during the printing process. This would need extra water, resulting in a wet mixture that could decrease the production printing rate per day and limit overhang structures due to the wet materials.

One challenge facing these materials is their slow drying process, especially in low temperatures and humid climates. However, the strength and stiffness of these materials are gained by time when water evaporates. Given the limited studies on the drying process during 3D printing, this research aims to explore the structural stability of maximum support-free overhangs using a custom-designed heating system based on Active Hot Air Drying System (HADS) that mimics sun drying. This system accelerates and aids the drying process of the layers, ensuring greater structural stability without deformation.

According to the results, the contentious heating system increased layer stability by reaching more layers at once. The maximum overhang reached was an angle of 50 degrees before failure at 60 degrees. In conclusion, the research highlighted and promoted the use of earth-based materials and offered some solutions to ensure that printed buildings could be dried fast. This is a solution to establish earth as a reliable material in structures in a contemporary way with the use of 3D printing.

Keywords –

Additive manufacturing; automation; 3D printing; earthen materials; support-free overhang

1 Introduction

3D printing (3DP) has been gaining more popularity in the construction sector for its ability to reach complex customized geometries without any formwork or support structure [1]. When it comes to using 3DP techniques in construction, the effect of the environment on the materials is a crucial topic to consider regardless of the drying process, in which both humidity and temperature play the main role. Most earthen-based materials used in 3DP require more water than conventional construction techniques such as rammed earth, adobe, and cob, which allows good printability and extrusion. Thus, this could be a problem for cold climates where extra time will be needed until the materials dry and the water vapour. In addition, the wet material would limit the amount of printed layers per day, which might decrease the production rate. Complex geometries are another limitation while the materials are wet. For instance, overhanging geometry, as a self-supported structure, is one of the main challenges in 3DP, as certain overhanging parts can compromise structural stability, especially when using slow-drying materials like earth. This typically limits design flexibility, reduces printing speed, and consequently lowers the daily production rate of printed layers.

Many researchers have investigated the maximum self-supporting overhanging geometry of earthen-based materials for 3DP, finding that the angle typically ranges between 17 and 20 degrees before failure [2, 3, 4]. The importance of studying the material's rheology allows controlling the climatic conditions that affect their internal bonding, which is responsible for the mechanical strength [5]. In 3DP with concrete, the material dries quickly, generating more layers per day and increasing the production rate. This occurs when concrete is exposed to air and reacts with chemical agents, such as admixtures and plasticizers. These additives alter the chemical formulation, resulting in a stiffer bonding material [5]. However, the concrete faces high drying shrinkage due to the high exposure, especially when the aggregates are not carefully selected [6]. When earth-based materials are exposed to air, they become stiffer over time as water evaporates, while the chemical composition remains unchanged [5]. Although cementation materials have been explored for their durability and the effects of additives added, yet, limited research covered the drying process of earthen materials during printing. Research done by [5] focused on the ”Forced Layer Drying” (FLD) technique to increase the mechanical properties of the wet mortar they used during printing. The results concluded that airflow, temperature, and geometry are factors affecting the evaporation rate, mechanical properties, and structure stability of the whole printed layers.

This research explores the feasibility of a custom-designed Active Hot Air Drying System (HADS) that aids in drying the layers during printing. The goal is to achieve the maximum stable overhanging angle with earthen materials, ensuring structural stability. The research method is tested on eight different inclination angles (Figure 2) of a modular overhanging arch using 3DP with clay as shown in Figure 1.

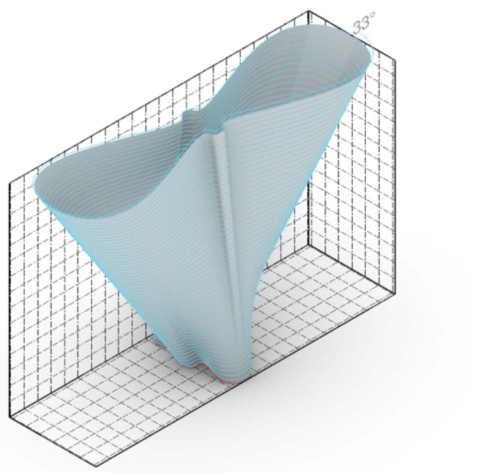

Figure 1: Overhanging example reaching 33° visualization inside 10mm grid. The object is 150 mm high and varies in length and depth depending on the overhanging angle

The printing and structural stability of the prototypes are tested both with and without an HADS. All the printing speed and flow rates remained constant. The results show that the heating system installed on both sides of the nozzle allows for achieving more overhanging arches at wider angles.

2 Related Work - 3DP drying process of earthen materials

Earthen materials typically require additional drying time to allow water to evaporate, unlike concrete. In 3DP, this challenge can impact daily productivity as layers rely on sunlight for drying. Unlike filament-based 3D printing, which requires cooling, the travel time between layers can affect bonding, leading to weaker connections and a drop in temperature [7].

Earthen material mechanical performance can be enhanced through several aspects; 1) adding admixture, alcohol, or alginate [5], 2) reducing the water content, which then could affect the extrudability of the layer. Yet both factors are affected by the climate, for example, a hot-arid climate allows water to evaporate faster than in a cold climate. Thus, the buildability will limit the printed layers from holding the upper layer until it dries and gets strength. It is important to mention the conflict between both printability and buildability for 3DP where pumping efficiency requires more wet materials which results in a lower strength, while buildability requires a material with a higher strength [5].

Architects are seeking designs that are innovative and cost-effective for their material optimization and stability without the need for any formwork. A research done by [8] produced a double-curvature façade panel by printing clay on a developed non-planar surface using a multi-forming machine with a movable actuator. This gives the flexibility to adapt the surface based on the customized geometry for each different tile without any waste formwork.

Research done by Motamedi et al. [5] implemented conductive heating through a heat gun with an 1800-watt and two heat guns with 3300 watts on two 30cm 3D printed clay blocks. The results show that the first experiment had a collapse at the 25th layer, while the second case reached higher layers with the 30th layer [5]. These results were done on a block with no overhanging consideration. A different drying process is done using infrared radiation to the deposited printed layer to allow increasing the past’s yield stress which the geometry keeps its shape [9]. Another study was conducted by [10] from IAAC, where a wooden formwork was used to support 3D-oriented clay overhanging at angles of 45°, 60°, and 75°, resulting in significant timber waste. Gomaa et al. [11] demonstrated in their research that cob, a mixture of earth and fibers, can be printed with overhangs up to 40 degrees. This finding indicates that fibers enhance the mechanical properties of the material, thereby improving structural stability. In our research, however, we will not incorporate fibers into the earth mixture.

2.1 State of the art

Building on previous studies, the effect of heat and self-supported overhanging angles on the stability of earthen materials remains unexplored. This will be the focus of our research. Accordingly, the heating process will be controlled after a specific number of layers to ensure the stability of overhanging geometries without causing cracking.

3 Method

To achieve the aim of this paper—creating structurally stable overhanging geometries with the maximum angle using earthen materials—an experimental method was developed. This method is based on a digital design-to-fabrication workflow and is divided into three main phases: geometry consideration, fabrication and assessment.

3.1 Geometry consideration and design parameters

The geometry was designed to achieve maximum overhanging through a balanced shape with a small area base of 27 x 64 mm, as shown in Figure 1 and 2. The total height is constant at 150 mm with a layer height of 1.7 mm and a total of 88 layers.

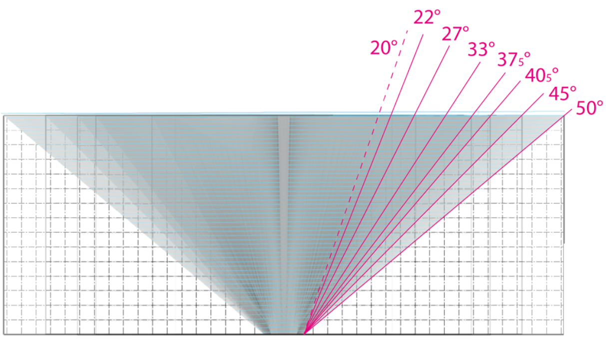

Figure 2. Inclination steps with a dotted line indicating the previously achieved maximum inclination of 20°

3.2 Fabrication

Nine prototypes were 3D printed using cla angles of 22°, 27°, 33°, 37.5°, 40.5°, 45°, 50°, and 60 assess which angle achieves the goal before failure, with and without HADS. A similar approach was ado based on the method outlined by [5]. They used tunnel experiment which act as a heating effec calculate the evaporation and drying rate of the mat while printing based on airflow speed and temperat with and without forced layer drying.

Accordingly, a HADS was added to both side the nozzle, with the assumption that it would impr structural stability by accelerating the drying of layers.

The first two angles, ranging from 17° to have been validated in previous research as the maxi achievable in clay printing [2, 3, 4]. This study, theref aims to explore new angles with the objective exceeding these limits to achieve stable geometries.

3.3 Setup

This robotic system is controlled by a computer running Rhino 3D, Grasshopper (GH), and the Machina plugin, which directly transmits URScript paths to the Universal Robot UR10. The robot is equipped with an end effector featuring a 3 mm nozzle and HADS on both sides. The clay is extruded from a cylinder cartridge by a motor, which is regulated by a controller (see Figure 4). This controller is directly connected to the UR's control unit. The parametric 3D model is sliced in Grasshopper, and the generated paths are merged and transferred via the Machina Bridge software.

3.4 Assessment

The structural stability of each prototype is measured within a setup (Figure 3 and 4) that hosts several tools. This begins with counting the maximum number of layers each prototype achieved before failure, using a grid installed behind the robot. A fixed camera was positioned in front of the model during printing. Additionally, a thermal camera was used to measure humidity, temperature, and water content in the layers to analyze the differences between each prototype.

3.5 Materials and Tools

The clay used is beige with Chamotte 20% 0 - 0,2 mm and JK Drop Spike [12] test of 3.5. A universal robotic arm (UR10) is used for 3D printing with a payload of 10kg and a nozzle size of 3mm. Flow rate was not calculated and is very depended on the nozzle size. The feed rate or the printing speed is 20mm/sec.

Two heater fans were installed on both sides of the nozzle to ensure consistent drying while printing. The heating system mimics the sun and air ventilation which increases the drying process of the layer. The heaters have not yet been designed to synchronize with the robotic arm, as each operates independently. Currently, the heater is manually activated. However, future adjustments could enable synchronization with both the robotic arm and the thermal camera, allowing for further experimentation.

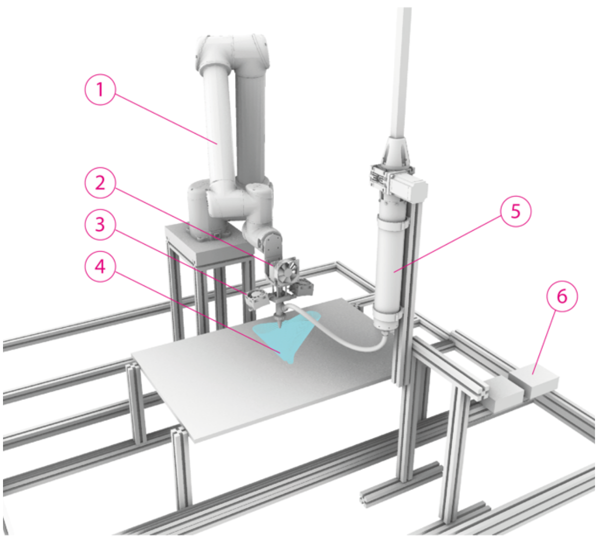

Figure 4. Experimental Setup: 1)robotic arm (UR10); 2)Screw-Extruder (custom-build); 3)PTC Fan Heater; 4)Test Object with inclined Overhangs; 5) Ram Extruder (custom-build); 6) Extruder controllers

4 Results & Discussion

4.1 The structure stability

Based on previous references, where the maximum stable inclination angle was documented as 20 degrees, it is acknowledged that this value can vary depending on the clay type and water ratio. The results showed that failure occurred at the maximum inclination angle tested. Our observations revealed that an angle of 22° remained stable without heating, while failure occurred at 27°. Table 1 compares the results for different inclinations with and without HADS, highlighting that all prints utilizing HADS were successfully completed, achieving angles up to 50°. Figure 5 illustrates the outcomes of the nine trials and the extreme overhangs achieved. Regarding stability, prototypes printed without HADS were observed to be overly wet, leading to loss of stability and self-deformation when moved from the bed post-printing. In contrast, prototypes exposed to HADS dried quickly, with layers bonding firmly to one another, resulting in greater stiffness. These prototypes retained their geometry and were easy to move, exhibiting behavior comparable to materials like PLA or ABS.

Although the research could have employed spiral continuous path planning, we deliberately decided to create a seam in the middle of the left overhang of the testing part. This decision was made to study the behavior of the printed object in the seam area, as shown in Figure 6. The 3DP process successfully achieved maximum overhang angles of 50°.

Table 1 Printing iterations

Angle	Drying System	Stable
22°	No	Yes
27°	No	No
27°	Yes	Yes
33°	Yes	Yes
37.5°	Yes	Yes
40.5°	Yes	Yes
45°	Yes	Yes
50°	Yes	Partially
60°	Yes	geometry fail

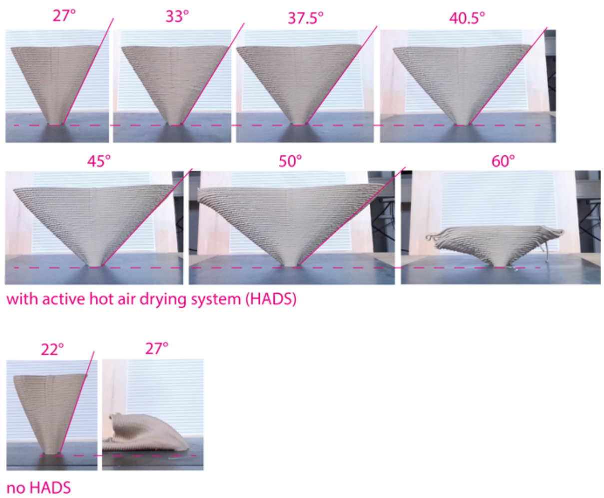

Figure 5. The different inclination angles printed with and without HADS

We assume that overhangs between 50° and 60° can be achieved which can be subject of further research. Both angles experienced failure on the seam side. This failure was attributed to the seam formed by the reverse extrusion after each layer, as illustrated in Figure 5.

Figure 6. The seam concept

This suggests that the HADS limit is 50° before failure occurs. While the 60° inclination did not result in failure, the layers did not align properly, which could be attributed to geometric limitations. At 45°, the layers overlap by 50%, indicating that further increases in inclination angles would likely lead to failure. This is due to the volumetric overlapping of the material, which shifts the geometry's center of gravity outside the footprint of its support. A similar issue could arise when validating the scalability of the prototypes on-site.

In the referenced paper by Motamedi, the overhang angle was achieved after 30 layers, heated with two heat guns, without collapsing. In contrast, our approach reached 88 layers. However, due to differences in the size of the printed material, these methods are not directly comparable. Scaling the nozzle increases both the material volume and the encapsulated humidity, requiring proportional adjustments in ventilation for effective heating. This should be further tested in future experiments.

Compared to the findings in [10], our prototypes underperformed, as their approach utilized formwork with angles ranging between 50 and 75 degrees.

4.2 Thermal Camera Temperature analysis

The monitoring of the prototypes during printing revealed a correlation between failures and the moisture levels of the layers. It was observed that the layers at the base were excessively wet, compromising their ability to support the weight of the layers above, leading to deformation. However, with the application of the HADS system, the temperature of the lower layers decreased, allowing them to solidify and better resist the loads from above. The HADS distributed heat evenly, ensuring that the entire printed body, rather than just the printed stripe, was surrounded by heated air, as shown in Figure 7. The thermal images show that the printing bed reflects heat, which supports the overall distribution of warm air. Although the surrounding area warms up to 36°C compared to the undried state at around 20°C, the object itself does not heat up and may even become cooler due to the heat-exchange effect. This assumption could be a subject for further research.

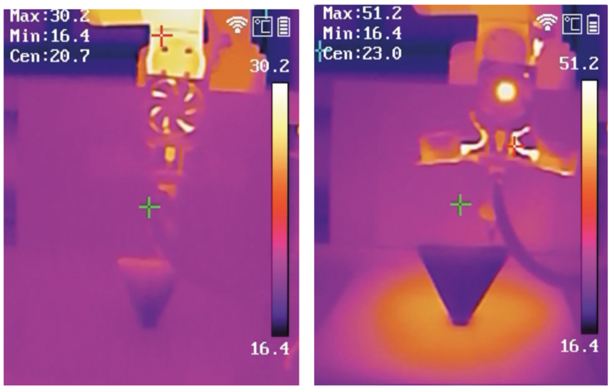

Figure 7. Thermal images. Left: 3DP without HADS. Right: 3DP with HADS

4.3 Limitation and further research

Although the printing speed was constant, it significantly impacted the structural stability especially when dealing with wet materials. Increasing the speed can lead to insufficient layer bonding, as the lower layers may remain too wet and unable to support subsequent layers. This can result in structural weaknesses and increased bucking and failure. Conversely, slower printing speeds allow for better moisture control and layer adhesion, enhancing the stability of the printed structure. Balancing print speed is, therefore, crucial for achieving optimal stability in 3DP clay components.

The room temperature was maintained at a constant 15°C; however, the same settings may exhibit different behavior when dealing with fluctuations in varying climates and humidity levels. Additionally, scaling up could impact the stability of the geometry, even if it is stable at a smaller scale. This is due to the increased volume in larger scales, which can affect the bonding between layers. Moreover, larger geometries may necessitate adjustments in printing parameters, such as speed and layer height, to ensure consistent quality and performance.

Furthermore, different clays can vary in their drying process which might cause cracks and uneven shirking problems by fast or unequal drying. Each clay should be tested and their percentage of water checked to observe the drying time and predict any cracks.

Concerning the technical issue, some failures occurred due to the seam observed on the one side of the object. Consequently, the design of the toolpath can influence the structural stability of the geometry, whether it follows a spiral path or a continuous path without reversal, as in our case.

Overall, scaling up necessitates careful consideration of these factors to ensure successful outcomes. HADS on a small scale could be durable, while on a large construction scale, we can rather find another way to absorb the humidity of the wall or ensure equal sun heat distribution across the whole building surface. The HADS process should be observed to prevent any cracking that might occur in the material.

Another recommendation for further research in large scale 3DP on-site is to add a larger heating system that can absorb the humidity from the large printed walls in the case of not controlling the sun distribution across the building surface especially when having the side of the building in the North direction where no sun is exposed on that side.

For further research, additional sensors could be integrated above the extruder to automate the HADS based on air humidity and the deformation of the printed output. Furthermore, a differentiated implementation of HADS could be explored, such as turning it off, or adjusting the temperature by reducing or increasing it on specific parts of the layer or object.

5 Conclusion

This research explored the maximum support-free overhanging angles that 3D-printed clay can achieve without additional support. Building on previous studies that reached a maximum of 20 degrees, our results surpassed this limit, achieving angles of up to 50 degrees with the implementation of the HADS. This new system ensured even heat distribution across the entire geometry, addressing challenges found in real-world applications where building surfaces, such as northern sides, are not naturally exposed to sunlight.

Our active hot air drying system, mounted on the printing head on a robot arm, ensures consistent heat distribution across the entire layer surface. This approach differs from previous studies that used handheld heat guns, which led to issues like cracking and shrinkage.

Looking ahead, this study raises further research questions, such as how the heating system would perform in humid or dry climates. Additional tests may be needed to adjust the water content in the clay and calibrate the heater temperature for optimal performance in different environmental conditions.

References

[1] Xie, F., Chen, L., Li, Z. & Tang, K. Path smoothing and feed rate planning for robotic curved layer additive manufacturing. *Robotics and Computer-Integrated Manufacturing* 65, 101967, 2020.

[2] IAAC, "Terraperforma Project," *IAAC - Institute for Advanced Architecture of Catalonia. Open Thesis Fabrication Program*, 2017. https://iaac.net/project/terraperforma/ (acc. Nov. 17, 2022).

[3] EL-Mahdy, D. & Ali, M. Assessing the solar radiation performance of self-shaded 3D-printed clay-based façades. *Architectural Engineering and Design Management* 20, pages 249–268, 2024.

[4] Cutajar, S. *et al.* Upscaling earth formworks: 3D printing strategies for material optimised reinforced concrete structures. *Constr Robot* 8, 3, 2024.

[5] Motamedi, M., Mesnil, R., Tang, A.-M., Pereira, J.-M. & Baverel, O. Structural build-up of 3D printed earth by drying. *Additive Manufacturing* 95, 104492, 2024.

[6] Mozaffari, S. *et al.* Digital design and fabrication of clay formwork for concrete casting. *Automation in Construction* 154, 104969, 2023.

[7] Hungria, E. B., Di Nisio, F. G., Cano, F. C., Voltolini, R. & Volpato, N. A study about weak intralayer bonding in extrusion-based additive manufacturing due to resumed extrusion during filling. *Polymer Testing* 140, 108595, 2024.

[8] Salem, I. Coupling Non-planar Robotic Clay Deposition with Multipoint Forming to Optimize the Manufacturing of Double Curved Façade Panels. in *Dokonal, W, Hirschberg, U and Wurzer, G (eds.), Digital Design Reconsidered - Proceedings of the 41st Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2023) - Volume 1, Graz, 20-22 September 2023, pages 499–508*, 2023.

[9] Ghazanfari, A., Li, W., Leu, M. C. & Hilmas, G. E. A novel freeform extrusion fabrication process for producing solid ceramic components with uniform layered radiation drying. *Additive Manufacturing* 15, pages 102–112, 2017.

[10] Coutinho, B.,Polvi, F., and Bryson, Z., "Temporary embedded supports for cantilevers and vaults in earthen 3d printing architecture," IAAC blog, 2021. https://www.iaacblog.com/programs/temporary-embedded-supports-cantilevers-vaults-earthen-3d-printing-architecture/ (accessed Nov. 14, 2024).

[11] Gomaa, M., Jabi, W., Veliz Reyes, A. & Soebarto, V. 3D printing system for earth-based construction: Case study of cob. *Automation in Construction* 124, 103577, 2021.

[12] Keep, J., JK Drop Spike - Clay Consistency MeasuringTool.https://wikifactory.com/@jonathankeep/jk-drop-spike. (accessed Nov. 20, 2024).