Robotic Imperfection Mitigation for 3D Printed Clay Voussoirs in Vault Structures

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This study explores the architectural potential of binder-free, 3D-printed masonry vaults constructed from interlocking clay voussoirs, combining digital form-finding, bio-inspired tessellation, and robotic post-processing. Building upon a prior investigation into interdigitated edge geometries informed by epidermal cells of Arabidopsis Thaliana, a novel workflow is developed to address the dimensional unpredictability of viscous clay in additive manufacturing. A compression-only funicular geometry was optimized through a generative loop involving Karamba, Kangaroo, and Galapagos. The resulting shell form was tessellated into stress-aligned, expanded-edge voussoirs and fabricated with Liquid Deposition Modelling. To resolve edge imprecisions inherent in clay extrusion, a robotic post-processing system was implemented. The interlocking system's performance was evaluated through both full assembly and staged disassembly, revealing emergent structural behaviours such as distributed force transmission through a larger span of voussoirs not only in perpendicular to the force flow but also in lateral direction. This preliminary study underscores the potential of two opposite manufacturing methods working in confluence that resolve into novel architectural and structural behaviors.

Keywords: *Vault Structure*, *Robotic Fabrication*, *Clay 3D Printing*.

INTRODUCTION

Throughout the history, vault construction has exemplified the convergence of geometry, material behavior, and construction technique. From the sun-dried mudbrick vaults of Mesopotamia to the intricately layered Catalan timber vaults of the Mediterranean, structural ingenuity has consistently emerged from the interplay of necessity and innovation (Van Beek, 1987; Davis et al., 2012; Block and Rippmann, 2013). These precedents reveal a nonlinear trajectory of technological evolution, shaped by adaptive responses to geographic, material, and cultural constraints (Lancaster, 2015).

In contemporary practice, this non-linear trajectory finds a new counterpart with integration of digital modelling, structural analysis and computerized fabrication. Architectural forms are becoming more driven by data as the 21st century requires designers to be more energy and environmentally conscious. Crucially, advent rapid prototyping workflows introduce a capacity for precision and complexity management that are co-aligned with the increasingly complex yet optimized solutions. Nonetheless, brick morphology has yet to be adopted with newly emerging manufacturing and computational tools. Additive manufacturing has opened possibilities for form-specific, resource-conscious, and structurally optimized construction methods that challenge the limitations of traditional masonry techniques. This convergence can be

perceived not merely as a technical solution, but as an epistemological shift, which can influence tools and materials in a performative and environmentally responsive solutions.

The point of departure is a previously published design experiment (Mansuri, Abdulli and Şen Bayram, 2024), which proposed a binder-free, single-layer vault assembled from 3D-printed clay voussoirs. Inspired by the interdigitated morphology of epidermal cells in Arabidopsis Thaliana, a custom edge-expansion algorithm was developed to enhance interlocking through topological continuity (Zhang, Halsey and Szymanski, 2011; Sampathkumar et al., 2014). Arabidopsis, a model organism in plant biology, is particularly notable for its irregular, puzzle-piece-like epidermal cells that evolve in response to distributed mechanical stress-forming patterns that increase intercellular adhesion and stress dispersion. Previous research on this natural formation being translated over to voussoir tessellation (Mansuri, Abdulli and Şen Bayram, 2024), the initial form-finding and tessellation logic showed potential, however the large-scale model of the vault failed
due to dimensional inconsistencies introduced during manual post-processing.

Rather than a setback, this failure served as a catalyst for the present study's central inquiry: Can the confluence of additive and subtractive manufacturing methods result in a complex yet precise brick morphology that has emergent structural performance in the form of compression only vault structure.

This question is pursued both as a technical challenge and a theoretical proposition, seeking to hybridize diverse systems of knowledge into a coherent, production-ready architectural prototype.

The advances in robotic fabrication and clay-based additive manufacturing have expanded the architectural potential of dry-assembled, binder-free masonry systems. Wang et al. (2017) introduced a hybrid workflow combining 3D-printed clay and robotic casting to achieve geometric complexity with material control demonstrating the importance of post processing for dimensional precision. Similarly, Darweesh and Rael (2024) proposed scaffold-free masonry vault construction using cooperative robots, emphasizing on-site adaptability and multi-robot coordination. These efforts parallel this research's approach in seeking reconfigurable and support-free structures. However, they focus on 3D robotic printed clay rather than hybridizing the potentials of two different techniques.

Interlocking systems have also seen renewed attention as a structural strategy. Mousavian, Bagi and Casapulla (2022) developed an optimization framework for joint shapes based on frictional resistance and structural feedback, which directly supports our focus on expanded-edge tessellation. Complementing this, Tavoosi Gazkoh, Lin and Zhou (2024) reviewed topological interlocking mechanisms in civil engineering, underlining their mechanical robustness and applicability in dry-stacked assemblies. Hua (2024) explored porous interlocking modules fabricated through digital stereotomy, offering performance-based insights into dry masonry applicable to our voussoir design. Although the binder-free aspects of research are similar to this paper's approach, they were not examples of 3D-printed clay.

Furthermore, Jin, Xu and Xu (2025) investigated clay-printed formwork integrated into green roof structures, highlighting how clay's material behavior can inform structurally active form-finding. This paper contributes to this growing body of research by uniquely combining biologically inspired tessellation, generative digital design tools, and robotic post-processing in a dual-stage fabrication process tailored to clay's inherent imprecision.

Different than the similar explorations, in this research, the resulting workflow leverages the precision of robotics, the intelligence of biological form, and the resource and performative potential of additive manufacturing to redefine masonry vaulting for the 21st century.

METHODOLOGY

The design-to-fabrication process was structured around three major phases, each containing a set of converging sub-stages: design & optimisation, prototyping & production, and post-production & assembly.

Design & Optimisation

A generative form-finding strategy was implemented by establishing an iterative loop integrating Karamba (structural evaluation), Kangaroo (form-responsive physics simulation), and Galapagos (evolutionary solver). Karamba3D is used to assess force distribution and identify principal stress trajectories within the funicular shell geometry. Kangaroo, a physics-based simulation engine, facilitates the dynamic mesh relaxation needed to approximate compression-only structures. Galapagos, a genetic algorithm solver, iteratively optimizes key design variables such as edge expansion ratios and tessellation dimensions to achieve a balance between structural efficiency and manufacturability. Selected solutions from the evolutionary algorithm were required to have a negative equivalent stress at each node of the simulation surface. Which generated a compression-only geometry suitable for masonry systems (Ripmann and Block, 2013). This sequence enabled the identification of shell configurations that consistently maintained compressive stress states with minimal displacement thresholds (Figure 1).

The selected geometry corresponded to a vault structure spanning 12x9 meters. It was defined by a form with elevated edge conditions, moderate enclosure avoiding excessive central height, and geometric qualities that were both structurally rational and visually coherent. The geometry's equivalent stress distribution was verified to remain within compressive limits when simulated with the mechanical properties of fired clay (Table 1).

Table 1
Mechanical properties of the Avanos clay (Mansuri et al., 2024).

Young's Modulus [kN/cm^2]	531
In-plane Shear Modulus (kN/cm^2]	212.4
Transverse Shear Modulus [kN/cm^2]	212.4
Specific Weight [kN/ cm^3]	17.0
Tensile Strength [kN/cm^2]	0.178
Compressive Strength [kN/cm^2]	-1.78

Upon completion of formal optimisation, a uniform thickness of 20 cm was assigned across the vault surface. This value was chosen to ensure structural resilience during post-processing and to meet manufacturing constraints observed during prototyping. Unlike earlier investigations (Mansuri, Abdulli and Şen Bayram, 2024), no further cross-sectional optimisation was pursued, in order to maintain robotic processing feasibility during trimming operations.

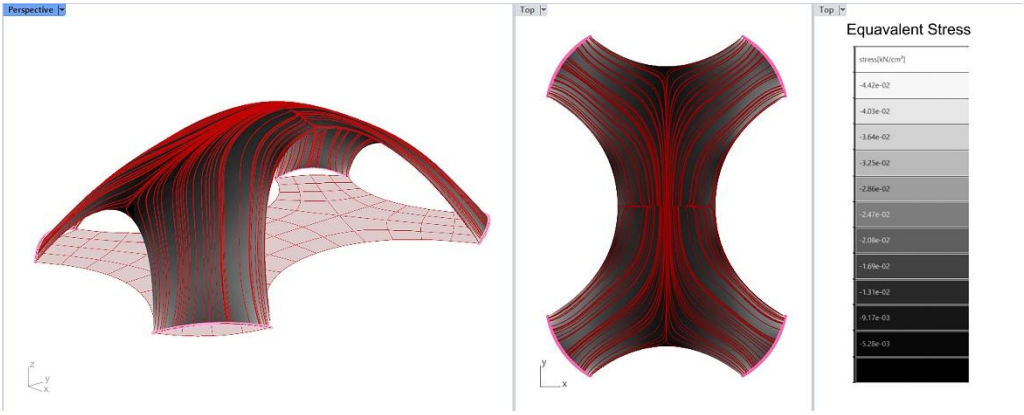


Figure 1
Form-finding process with Karamba analysis Showing compression only surface geometry (Authors, 2025).

Following the assignment of thickness, the vault surface was tessellated into voussoirs. Their boundaries were manually aligned to remain perpendicular to principal stress directions extracted from Karamba simulations, ensuring that each unit could effectively transmit loads in compression (Figure 2).

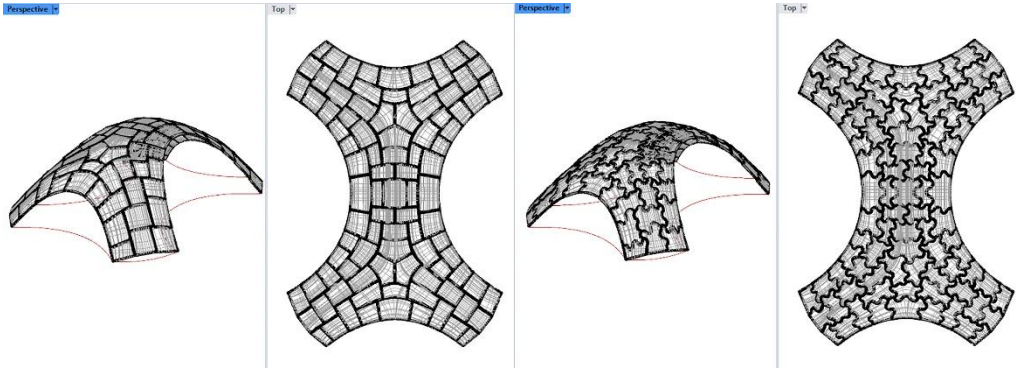


Figure 2
Initial voussoir tessellation informed by the principal stress lines (Authors, 2025).

Subsequently, an edge expansion algorithm was applied to the voussoir tessellation, consistent with previous study (Mansuri, Abdulli and Şen Bayram, 2024). Unlike traditional voussoir configurations with planar faces, the expanded geometry allowed for force distribution to extend beyond immediate neighbors (Zhang, Halsey and Szymanski, 2011). This approach mirrors how epidermal cells of Arabidopsis thaliana develop puzzle-shaped boundaries that redistribute tensile forces along curved cell walls. In the architectural context, this interconnectivity enabled by expanded edges reduced the need for extensive scaffolding, allowing a stable, self-supporting structure to be realized through dry assembly.

To prevent uncontrolled growth during edge expansion, the expansion algorithm was manually constrained based on anchoring and subdivision rules informed by the vault's force flow diagram and initial tessellation corner positions. It was made sure that all of the contacting edge surfaces were constructed from two sections ensuring a perpendicular ruled surface is in contact between voussoirs (Figure 3).

Prototyping & Production

Toolpaths were generated based on the expanded geometry, considering expected material shrinkage (~ 10%) (Abdulli, 2024) and post-processing loss (~5mm). Accordingly, external boundaries were deliberately overbuilt, resulting in an approximate wall thickness of 10 mm at the edges.

Internal infill densities were modulated between 40% and 70%, depending on local stress concentrations within each voussoir. This gradient was designed to echo the behavior of cytoskeletal microtubules observed in Arabidopsis thaliana cells,

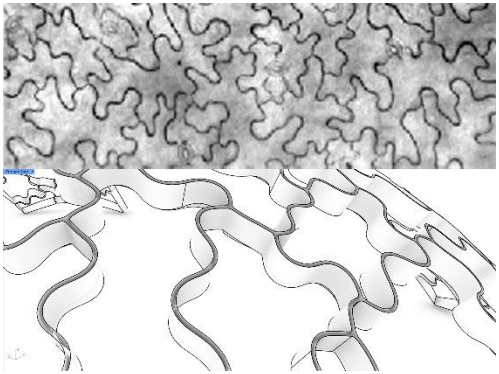


Figure 3
Edge expansion algorithm being applied over the initial voussoirs. (Top image is from Zhang, Halsey and Szymanski, 2011; bottom image, Authors, 2025)

where internal reinforcement aligns with mechanical stress patterns (Zhang, Halsey and Szymanski, 2011; Sampathkumar et al., 2014). Tool path orientation was similarly adjusted to follow principal stress lines, enhancing the structure's compression capacity.

3D printing and Robotic Milling processes were kept in mind during the realization of these geometries, specifically ensuring that no overhangs were present during 3D-printing and a sectional milling operation can easily trim ruled surfaces with straight cross sections in a single pass.

The production phase was carried out in two distinct stages: initial SLA prototyping and full-scale clay 3D printing.

In the first stage, the newly developed vault geometry was prototyped at 1:20 scale using SLA printing technology. This preliminary model allowed the verification of interlocking tolerances and geometric integrity prior to full-scale production (Figure 4).

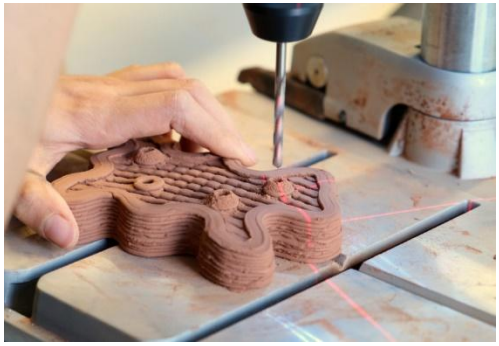
Figure 4
1:20 scaled SLA Prototype (Authors, 2025).

Figure 5
Drill press adjustment of connection holes (Authors, 2025).

Subsequently, LDM manufacturing was performed using a custom-made delta 3d printer for clay printing, calibrated for large scale fabrication. A locally sourced clay body from the Avanos region, which is well known for its combination of plasticity and strength, making it especially suitable for additive manufacturing. To adapt the material for extrusion-based deposition, additional water content was incorporated into the clay mix to enhance flowability during printing.

A total of 93 unique voussoirs were produced over a period of three days. Individual print durations ranged between 25 to 45 minutes, with an average print time of 35 minutes per unit.

Following an initial drying period of 6 days, each printed unit was subjected to a post-processing refinement step. Connection holes designed for robotic trimming jigs were mechanically adjusted using a drill press to correct for minor deformations that occurred during deposition or early-stage drying (Figure 5).

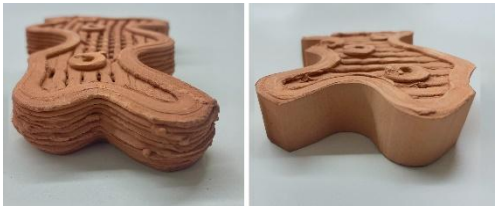


Each block was mounted on a custom MDF jig that held it 11 mm above the working table. This clearance allowed the robotic tool unrestricted access to the surfaces requiring refinement. The holes were sized to accommodate MS bolts and positioned to ensure that the entire surface area of the voussoirs remained accessible during trimming (Figure 6).

Figure 6
Piece positioning onto MDF jig (Authors, 2025).

Post-Processing &Assembly

Prior to the initiation of robotic post-processing, a series of tests were conducted to determine optimal parameters for material condition, toolpath speed,

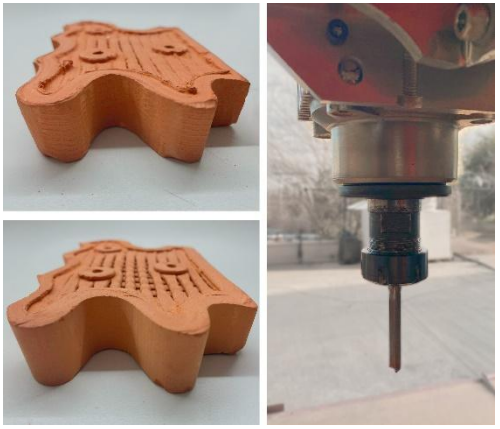


and end mill type. It was determined that machining should be performed on unfired clay components, as the material is significantly more machinable in its green state and allows for faster and more efficient production process. To assess the ideal timing within the drying process, comparative tests were carried out on samples in both leather hard and bone-dry conditions. Spindle speed and tool feed rate were held constant across these tests. Results indicated that the bone-dry state offered the highest dimensional stability and jig compatibility for robotic trimming since the leather hard clay continued to shrink after machining leading to unsuccessful joinery between voussoirs.

A second set of tests was conducted to determine optimal pace and feed speed values. Using bone-dry material samples, a series of trials was performed under varying movement and spindle speed combinations. The most favorable outcomes were achieved using a 6000-8000 rpm spindle speed and 200-300 mm/min speed, providing both efficiency and precision without damaging the parts (Figure 7).

The third set of trials focused on identifying the appropriate end mill type. Under consistent material and speed conditions, two types of tools were evaluated: a 6 mm helical ball-end 3-flute tool and a 10 mm straight 2-flute flat down cut end mill. Although the ball-end mill offered geometric conformity, its pointed tip increased operation time and failed to deliver sufficient surface quality. Conversely, the straight-end tool, which engaged the work piece with its side edges, proved better suited for trimming the ruled surfaces of the voussoirs, producing superior results both in terms of speed and finish quality (Figure 8).

The finalized geometry and fixture system were imported into SprutCAM software, where a single pass swarf tool path was generated for each unit. The toolpath simulations were executed using a 6-axis



KUKA KRC robotic arm mounted on a fixed base, using the previously validated tool, speed, and pacing parameters. Following successful collision free simulations, robotic trimming of all 93 parts was executed over a total duration of 6 hours with each piece taking approximately 2-4 minutes. The resulting parts exhibited high edge fidelity and dimensional accuracy (Figure 9).

Figure 7
On left; raw piece without post process, on right; refined piece with optimum test parameters (Authors, 2025).

Figure 8
On top left; test result with ball-end tool, on bottom left; test result with straight end mill, on right; selected end mill (Authors, 2025).

Figure 9
Piece refinement with KUKA (Authors, 2025).

Machined pieces were fired in kiln at 950 C over 9 hours. After the firing process, the assembly was performed by a team of two, who completed the structure within minutes. The Holes that were used in the mounting process of the tiles on the MDF board were used again to group panels with plastic zip-ties temporarily until the completion of the assembly (Figure 10).

Figure 10
Assembling the pieces (Authors, 2025).

Due to the effectiveness of the edge trimming process and grouped assembly method, all components were successfully assembled without scaffolding or binders with ease (Figure 11).

FINDINGS & DISCUSSION

To evaluate the structural coherence of the assembly beyond initial load-bearing behavior, a controlled disassembly process was undertaken. Individual voussoirs were systematically removed from the completed vault prototype in order to assess whether the interlocking system exhibited adaptive characteristics analogous to those observed in epidermal plant cells, the capacity to maintain structural continuity under localized disturbance. Remarkably, the structure retained its overall integrity well into the later stages of disassembly, indicating a high degree of distributed load transfer and systemic redundancy within the interlocking mechanism (Figure 12).

Disassembly experiments revealed that lateral force paths extend across multiple adjacent voussoirs, highlighting a form of passive load redistribution. Upon the removal of individual units, the structure remained self-supporting due to frictional engagement and expanded edge geometry. While quantitative load testing was beyond the scope of this phase, observational data suggests the interlocking geometry contributes to robustness against localized failure.

Figure 11
Finalised vault (Authors, 2025).

Figure 12
Disassembling process (Authors, 2025).

These results suggest that the edge-expansion algorithm not only facilitates dry assembly but also contributes to emergent stability through indirect stress transmission effectively diffusing loads across neighbors, rather than limiting force flow to immediate adjacencies. This behavior reflects the architectural potential of decentralized logic-where robustness emerges not from reinforcement or adhesion, but from patterned interdependence.

Although edge expansion algorithm improves stability of the vault structure as it was observed in all model assembly processes, further research needs to be done. When epidermal cells of arabidopsis thaliana are examined, there is a differentiation between the central and edge cells. This differentiation could be used to further improve the structural performance of the interdigitated voussoir system. In addition, there are numerous other research being done in terms of structural performance under seismic scenarios (Barentin, Van Mele and Block, 2018) similar research needs to be conducted for further understanding of the potential benefits of interdigitation within voussoirs.

In terms of manufacturing process of highly complex voussoir morphology, the difference between the present vault and the previous experiment (Mansuri et al., 2024) was decisive Whereas the initial prototype collapsed during mid-assembly due to cumulative tolerance mismatches and imprecise manual trimming, the current version maintained both geometric and load-bearing stability throughout. Post-trimming voussoirs clearly enabled completion of a binder-free, scaffold-less shell by a team of only two. It was observed that this confluence-driven approach yielded benefits not only in structural performance but also in the production and assembly phases. Robotic post-processing enabled a level of precision and consistency that significantly reduced cumulative fabrication error. The dry-fit assembly was completed without the need for scaffolding or secondary reinforcement, validating the hypothesis that biologically informed interlocking geometries can serve as viable tectonic system.

This production was scaled to meet constraints related to robotic work-cell size, material throughput, and controlled test conditions. While limited in span, it enabled precise evaluation of geometric fitting, fabrication tolerances, and structural interlocking behavior. Future research will address the translation of this method into larger-scale architectural prototypes to assess full structural viability and on-site constructability.

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This production is currently being presented at the Venice Architecture Biennale 2025 in the Türkiye Pavilion “Grounded” until November 2025 (Figure 13). We’d also like to thank IKSV and the Curators for the selection and their positive approach during the process, and our Biennale sponsor Lütfü Erman

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Figure 13
The vault presented at Venice Architecture Biennale 2025, in the Türkiye Pavilion "Grounded" (Authors, 2025).

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