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# Demountable Architectural Interventions: Reusable Robotic Moulding and Waste Reduction in Interlocking Concrete Structures

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## Abstract

As the discipline of architecture evolves, there is an urgent need to bridge the gap between complex digital design paradigms and sustainable fabrication. This paper investigates the innovative potential of Topologically Interlocking Assemblies (TIAs) through a synergy of material computation and robotic fabrication. TIAs offer a structural approach where blocks are held together solely by their geometric configuration and boundary constraints, functioning as self-supporting systems without traditional adhesives. Focusing on a 1:1 scale structure, this project introduces a lightweight concrete mixture incorporating perlite and soil that reduces block density to 50% of the normal range while maintaining compression strength. Central to the methodology is a robotic 3D-printing workflow used to create bespoke, reusable PLA formworks. By rationalizing diverse block geometries into four unique modules, the workflow enabled the precise casting of complex osteomorphic components while drastically reducing construction waste. The final prototype demonstrates a modular, binder-free assembly that promotes the recycling of formworks and structural components. The results establish a new design paradigm where material efficiency, interlocking assemblies, and robotic fabrication converge to produce high-performance, demountable architectural interventions.

**Keywords**: Topological Interlocking Assemblies (TIAs), Computational design, Robotic 3D Printing, Compression structures, Sustainable construction, Light Weight Concrete Mix.

## 1. Introduction

As the discipline of architecture evolves, there is an urgent need to bridge the gap between complex digital design paradigms and sustainable physical fabrication processes. Contemporary architectural assemblies rely heavily on carbon-intensive adhesives, mortars, and chemical binders that effectively lock disparate materials together, rendering future separation and reuse nearly impossible. This research, conducted within an intensive London-based research workshop titled AA DLAB 2025 dedicated to the advancement of contemporary architectural practice, investigates a paradigm shift toward reversible assembly. By eliminating permanent bonding agents, the study explores how robotic precision can be utilized to create dry-jointed, interlocking geometries that achieve structural stability through form and friction alone. Such binder-less systems allow for the pure recovery of materials at the end of a building's lifecycle, transforming the built environment into a temporary material bank rather than a source of future waste. Central to this shift is the implementation of Topologically Interlocking Assemblies (TIAs). TIAs offer a sophisticated structural approach where constituent blocks are held together solely by their geometric configuration and boundary constraints, functioning as self-supporting systems without traditional adhesives. This mechanical interlocking is often achieved through the use of osteomorphic blocks, modules characterized by concavo-convex geometries that ensure local equilibrium and global stability. Seminal research by Dyskin et al. [1] established that these mortarless structures are uniquely resilient due to their ability to dissipate energy through the micro-movements of individual blocks, making them highly effective for seismic-resistant and demountable applications. Furthermore, Giuseppe Fallacara [2] highlights how traditional stereotomy, when combined with contemporary digital tools, enables the creation of complex, interlocking masonry that challenges conventional assumptions regarding material permanence.

However, the fabrication of these complex modules presents a significant environmental hurdle. To achieve the necessary locking logic, modules often require unique formal geometries across the structure. Traditional casting of these bespoke modules requires many unique formworks, which typically increases the use of material and construction waste. To address this, the project focuses on the design and production of a 1:1 scale structure that optimizes fabrication complexity and material weight. The research introduces a lightweight concrete mixture incorporating cement, perlite, and garden mulch, which reduces the density of the mix to 50% of the normal range, thereby lowering the carbon impact and self-weight of the structure. The innovation of this study lies in the integration of robotic 3D printing to create bespoke, reusable formworks. As explored by Jipa et al. [3], additive manufacturing offers a superior method for creating complex moulds that would otherwise require labor-intensive CNC milling or timber stiffeners. By rationalizing the diverse geometries into four unique module categories and 35 total components, the team enabled precise casting while drastically reducing the number of unique moulds required. These formworks, printed in Polylactic Acid (PLA), utilize a binderless design of their own, slotting together for rapid assembly and disassembly without secondary fixtures. This integration of robotic precision and reusable moulding transforms the fabrication of intricate TIA modules into an economically viable and sustainable practice. Ultimately, the results establish a new design paradigm where material efficiency, funicular form optimization, and robotic fabrication converge to produce high-performance, demountable architectural interventions. While the underlying structural physics of topologically interlocking blocks are well-documented, the scientific novelty of this research lies in the closed-loop integration of large-format additive manufacturing (LFAM) with geometric optimization. This workflow successfully overcomes the historic bottleneck of stereotomy, the high cost and material waste of bespoke formwork, by establishing a reversible, multi-part, reusable tooling system that makes non-standard compressive assemblies economically viable.

## 2. Methodology

The research methodology is structured to bridge the gap between computational exploration and physical performance through a cohesive three-stage workflow: computational experimentation (form-finding), structural optimization, and robotic fabrication. This multi-scale exploration addresses the complex interactions within Topologically Interlocking Assemblies (TIAs) at both the component and global levels to ensure structural continuity and fabrication viability.

### 2.1. Multi-Scale Computational Exploration

The computational approach followed an iterative logic where geometry and structural performance evolved in parallel through continuous feedback between parametric modelling, rigid-body simulation, and physical prototyping. Rather than conceiving assemblies as static joints, the project approaches them as dynamic interfaces for load transfer and force distribution. This shift allows for the integration of digital manufacturing processes early in the design phase, promoting waste reduction and lifecycle optimization. The core structural logic of this research is rooted in the principles of topological interlocking assemblies by Dyskin et al. [1], which increases structural resilience by fragmenting the material into small-scale elements that arrest crack propagation at the interfaces. As explored by Weizmann et al. [4], the architectural application of TIAs requires a procedural understanding of how local kinematic constraints, derived from two-dimensional tessellations, can be transformed into three-dimensional interlocking polyhedra. For the global configuration, research explored various geometric figures, ultimately incorporating the catenary curve to optimize the transmission of compressive loads. This funicular approach is essential for TIAs, as these structures achieve stability only when the global geometry remains in complete compression, as demonstrated in recent studies of funicular arches using topological assemblies by Sheth et. al [5]. Following the structural principles of Robert Hooke and Antoni Gaudí, the catenary form was utilized to minimize bending stresses while remaining consistent with the interlocking logic of the assembly (Figure 1).

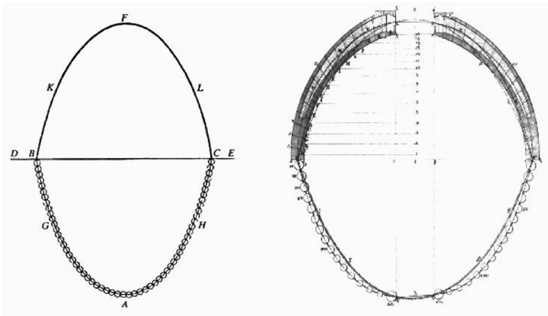


Figure 1: (Left) Poleni's drawing of Hooke's analogy between an inverted arch and a hanging chain, and (Right) Poleni's structural stability analysis of the Dome of St. Peter's in Rome, 1748

Early parametric models systematically tested variations in contact surface curvature, rotation angles, and interface typologies, resulting in a digital catalogue of configurations evaluated for stability and constructability (Figure 2). To optimize material efficiency, the self-weight of the modules was reduced by introducing internal voids and incorporating perlite into the concrete mixture. Preliminary iterations revealed that TIAs are highly sensitive to geometric precision; models with excessive spatial boundaries or high module variation often failed to achieve equilibrium during rigid body simulations.

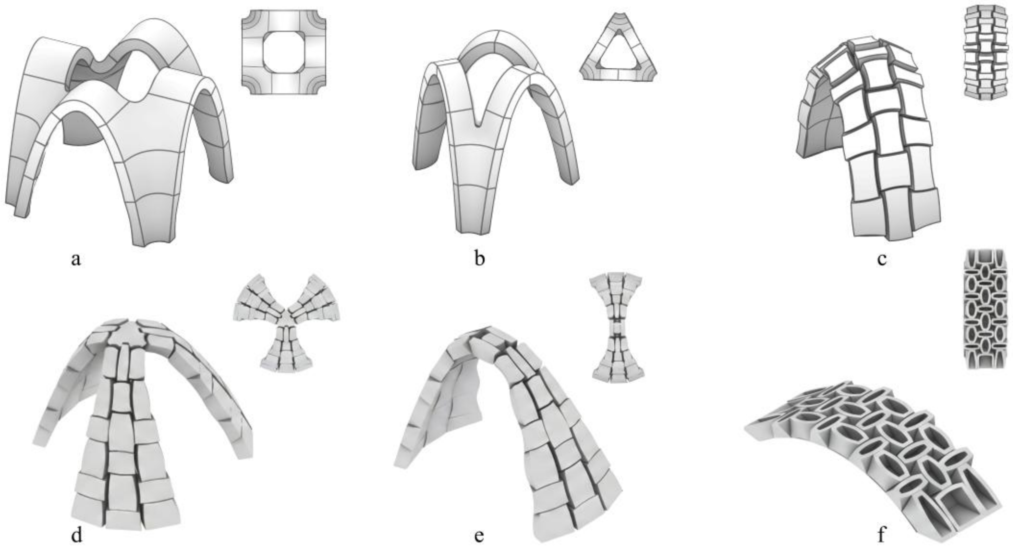

Figure 2: Early design explorations. a) Four catenary arches with tessellated blocks b) Three catenary arches with tessellated blocks c) Single catenary arch with osteomorphic blocks d) Three concentric catenary arches with osteomorphic blocks e) Single concentric catenary arch with osteomorphic blocks f) Single catenary arch with optimized osteomorphic blocks

### 2.2. Component Scale VS Global Scale

The transition from digital exploration to physical prototype was a non-linear process that necessitated a reconciliation between geometric idealization and fabrication constraints. Initially, the system converged on a configuration of 27 components across 10 unique modules within a 3×3×1 m bounding box. While this was the first iteration to achieve self-supporting behaviour in rigid-body simulation, the high degree of module variation presented significant fabrication challenges regarding casting time and material waste. To ensure fabrication efficiency, the system was optimized into a final configuration of 35 components derived from only four unique module types (Figure 3).

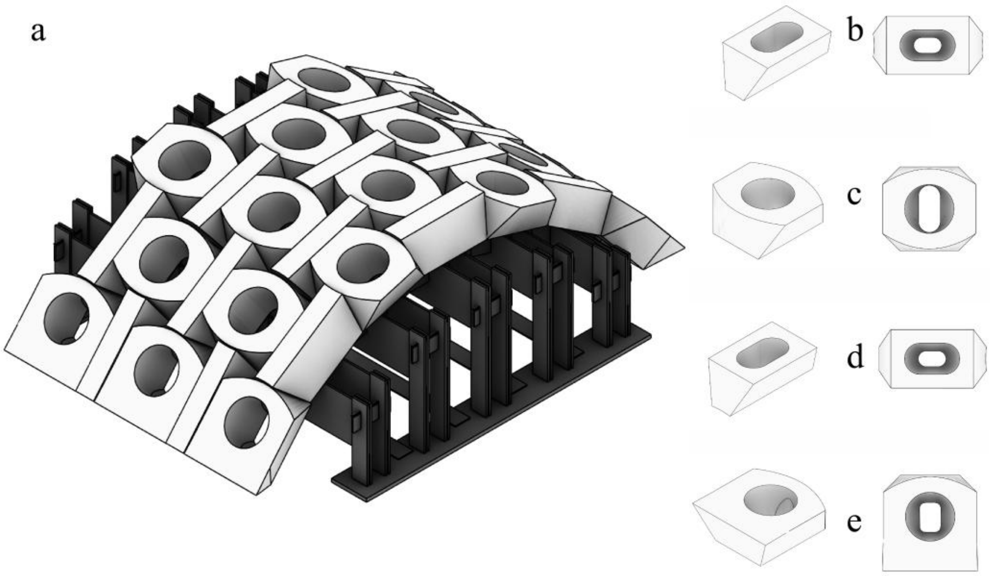


Figure 3. a) Global final structure of 35 blocks with support scaffolding for assembly b) Module 1 with total count of 13 c) Module 2 with total count of 12 d) Module 3 (footing) with total count of 4 e) Module 4 (footing) with total count of 6.

This reduction allowed for a more sustainable moulding strategy without compromising the structural continuity of the interlocking system. To evaluate the structural performance of these discrete blocks, the team utilized generative computational workflows. Evolutionary optimization was performed using the Wallacei plugin by Makki et. al [6] for Grasshopper to find an equilibrium between geometric parameters and structural stability. Furthermore, Finite Element Analysis (FEA) was conducted via the Karamba3D plugin [7] to map principal stress lines for mass reduction. This enabled the identification of critical compression zones and potential stress concentrations within the osteomorphic interfaces as well as informing the size of the voids per each block, ensuring that the self-locking geometry effectively resisted the internal forces of the funicular form. In parallel, rigid-body dynamics were simulated using the PhysX engine [8] to predict post-assembly behaviour, specifically the displacement of blocks as they settle under gravity. The results indicated a distinct gradient of movement: blocks at higher elevations exhibited greater settlement distances, while those nearer to the footing remained stable. Collectively, these multi-scale analyses provided a predictive model for assembly dynamics, allowing the team to anticipate the physical interactions of the 700+ kg assembly before physical construction commenced (Figure 4).

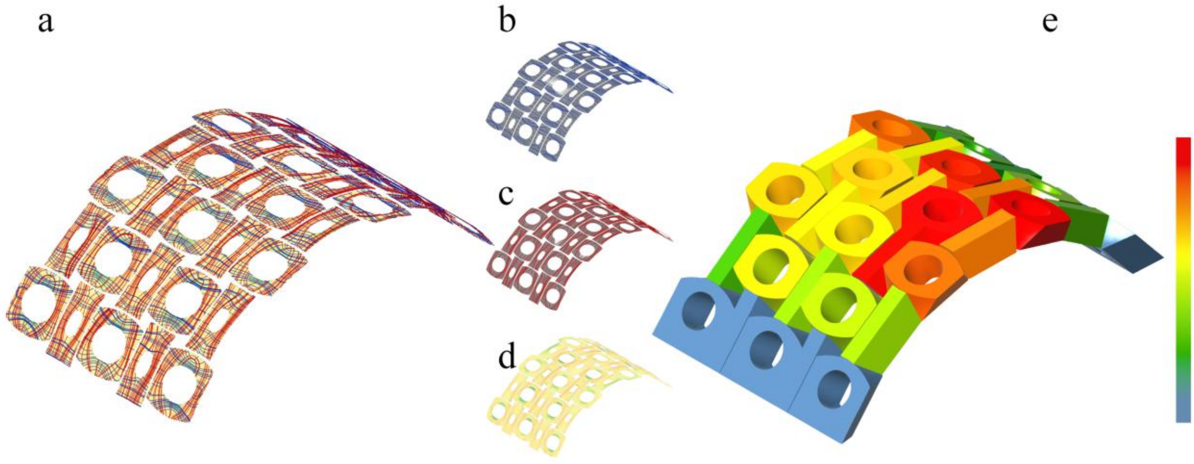


Figure 4. a) Principal stress lines of the final assembly b) Tension c) Compression d) Shell stress e) Rigid body simulation of the assembly indicating a maximum block displacement of 70 mm to reach structural equilibrium.

Additionally detailed FEA indicated the maximum displacement recorded at the thrust line middle is small, peaking at just $6.22\times10^{-3}$ cm. This implies a highly rigid structural system. The reaction forces at the base are well distributed, ranging from a maximum compression of -8.09 kN to a maximum tension of 6.57 kN. The presence of both positive and negative values shows a clear division of support conditions under load, where negative values indicate compression downward into the supports, and positive values indicate tension or potential uplift tendencies at the outer boundaries. The stress distribution ranges from a maximum compressive stress of -2.87N/mm$^2$(MPa) to a maximum tensile stress of 0.81 N/mm$^2$. These values are exceptionally low, making them highly compatible with alternative low-strength construction materials, which typically perform well under low compressive regimes. The low tensile stress of 0.81MPa also minimizes the risk of structural cracking or separation in binderless, interlocking assemblies.

## 2.3. Robotic 3D Printing for Reusable Formworks

The core fabrication innovation of this research is the development of a robotic 3D-printing workflow designed to eliminate the material waste and labor-intensive assembly typically associated with bespoke concrete formworks. To accommodate the geometric complexity of the osteomorphic modules, each mould was rationalized into four discrete parts: a locating base, a central plug, and two side panels. These components were designed to slot together using binderless logic, requiring no secondary fixtures for assembly, which aligns with the project's overarching theme of reversible construction (Figure 5). While the interior interfaces utilized mechanical slotting, the exterior of the side panels were secured with simple clamps to resist the hydrostatic pressure generated during the casting of the concrete mix. The digital workflow utilized Rhino/Grasshopper for geometric design, while robotic toolpath programming was executed via Aibuild CAM software [9]. To ensure printability and successful demoulding, all modules were designed with a maximum 45-degree printing angle and significant draft angles on the base and plug components. Fabrication was carried out using a Massive Dimension MDPE10 fused granulate fabrication (FGF) system mounted on a KUKA KR30-3 robotic arm. This Large Format Additive Manufacturing (LFAM) approach allows for significant scalability in future architectural applications.

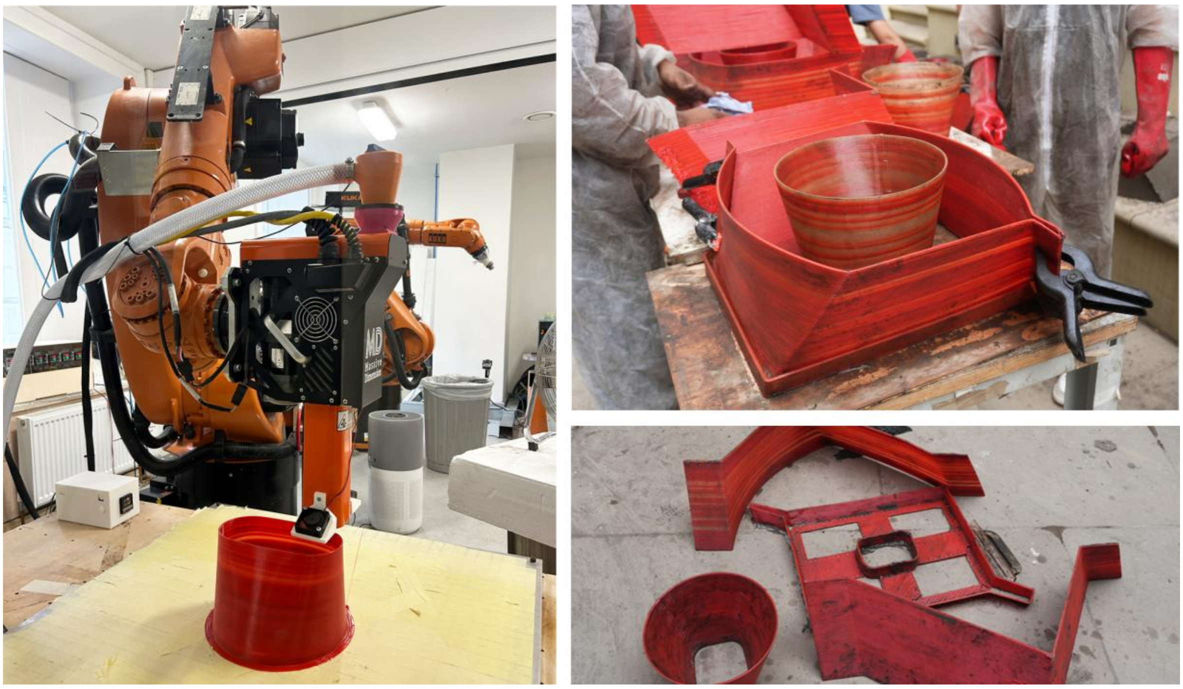

Figure 5. Robotic 3D printing of reusable formworks utilized for the concrete casting of osteomorphic interlocking blocks.

The formworks were printed using Polylactic Acid (PLA), a renewable and industrially biodegradable thermoplastic. Recent studies by Jipa et. al [3] in robotic additive manufacturing highlight that FGF processes significantly reduce production time compared to standard filament-based printing. In this study, the total printing time for a complete four-piece mold was 2.5 hours. The wall thickness was set to 4.5 mm to provide the necessary structural stiffness to resist deformation during casting. Although minor deflection occurred due to hydrostatic pressure, the choice of 3D printing proved superior to traditional CNC-milling or timber fabrication, which would have required significantly more time and material waste to achieve the same geometric complexity. As noted by Jipa [10] 3D-printed formworks represent a critical shift toward geometry-based material efficiency in concrete construction. Furthermore, the ability to reuse these PLA molds for multiple casting cycles, achieving a rate of three blocks per day per mold, establishes a sustainable alternative to single-use formwork systems.

### 2.4. Material Experimentation

Special importance was given to the material composition of the modules to ensure a reduction in both the carbon footprint and the overall self-weight of the assembly. In an effort to deviate from standard carbon-intensive concrete, traditional aggregates were substituted with more sustainable and readily available natural materials. Specifically, gravel was replaced with perlite to act as a lightweight aggregate, while sand was substituted with local soil (earth). To facilitate the rapid fabrication cycle required for the 35-component assembly, a fast-setting cement was utilized, enabling a production rate of three blocks per mould per day. The resulting lightweight concrete mixture followed a specific volumetric ratio of 5:15:8:1 (Soil: Water : Cement : Perlite). This composition successfully reduced the density of the mix to approximately 50% of the standard concrete range, effectively lowering the structure's total mass to roughly 700+ kg. As noted by Topçu [11], the incorporation of perlite is a proven strategy for producing semi-lightweight concrete with enhanced thermal properties and reduced dead loads. Furthermore, the integration of soil as a primary filler aligns with recent advancements in cement-stabilized earth blocks, which offer a significant reduction in embodied energy compared to traditional masonry. The use of garden mulch was also explored as a secondary additive to further reduce carbon impact and density. While the inclusion of organic matter can affect the structural integrity of cementitious mixes, recent research into bio-composite cements suggests that carefully calibrated organic-to-binder ratios can maintain the necessary compressive strength for low-rise architectural interventions [12]. The material experimentation phase confirmed that the 5:15:8:1 ratio provided the necessary structural continuity and edge definition required for the osteomorphic interlocking faces.

## 3. Fabrication and Assembly

The transition from digital simulation to physical realization for Topologically Interlocking Systems (TIAs) requires a rigorous management of tolerances and material behaviour. Unlike computational models that operate under ideal conditions, the physical assembly of the 1:1 scale prototype faced challenges related to manual casting deviations, assembly friction, and lateral momentum.

### 3.1. Prototyping and Moulding

To mitigate the risks of global instability, a series of 1:5 scale models were produced using PLA-printed osteomorphic modules to validate the assembly logic and surface contact angles (Figure 6). These early prototypes confirmed that the concavo-convex geometry requires high surface accuracy to ensure effective load transfer as well as a precise assembly sequence to enable the formation of the global form. Full-scale production utilized the 3D-printed modular formworks, which were oiled to ensure a smooth demoulding process. Each mould was assembled and casted with concrete and left to be dried in approximately 3 hours. By utilizing fast-setting concrete within the 5:15:8:1 mix ratio, the team achieved a throughput of three blocks per mould per day. To further reduce the overall mass of the 700 kg structure, all modules were designed with a central void, effectively decreasing the volume of material required without compromising the interlocking surfaces.

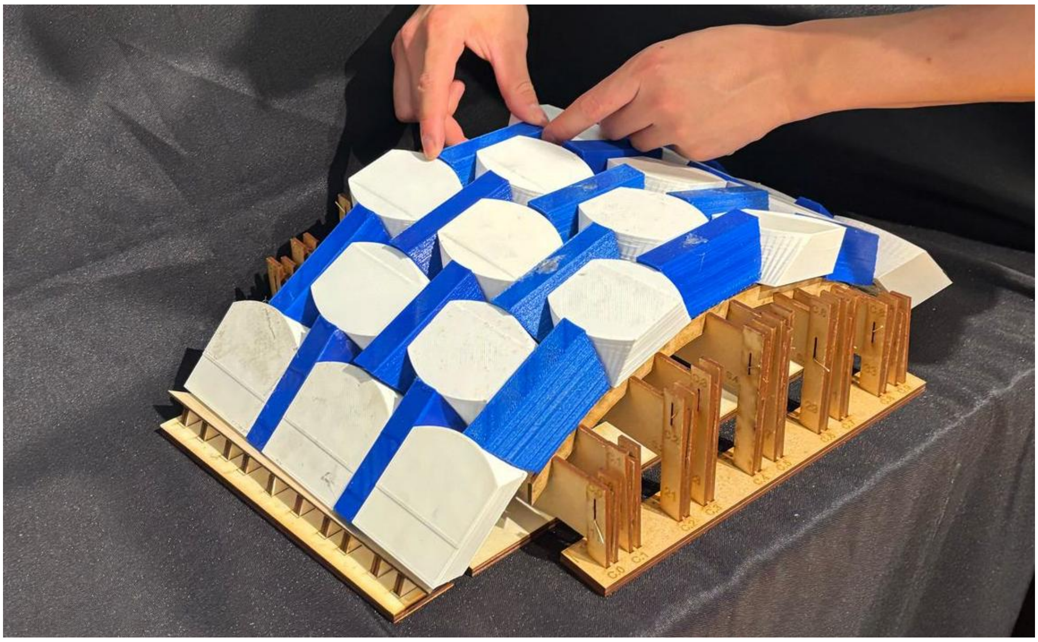

Figure 6. Scaled physical prototype developed to investigate the programmatic assembly sequence and initial structural stability.

### 3.2. Custom Base and Tensioning System

As the global geometry of the structure follows a segmented arch logic, a custom base was engineered to prevent lateral spreading. The base consists of two separate footings that support the bottom row of modules at a specific angle of 107° to translate the compressive loads directly to the ground. To counteract the outward thrust of the arch, a series of 4 mm diameter galvanized steel wire ropes, each with a Maximum Breaking Load (MBL) of 7 kN, connected the footings in tension. This tensioning system ensures that the system's loads are distributed homogeneously across the binder-less interfaces.

### 3.3. Scaffolding and Assembly Sequence

The assembly required a specialized scaffolding system designed to support the 700 kg+ load while allowing for the incremental settling of the modules. The scaffold was constructed from interlocking CNC-cut OSB ribs oriented in both X and Y directions, providing four linear support points for each block. This design allowed the ribs to be lowered individually, ensuring that each row of modules could settle into the next to lock the system into equilibrium. The assembly followed a specific inside-out sequence: The team began with the middle arch (arch 3 out of 5 arches), placing the bottom-most pieces on the footings. Successive pieces were added symmetrically per arch, with the top piece acting as a central keystone to secure the arch segment. Using the same logic, other arches on two sides of the middle arch were placed, followed by the final peripheral rows at two ends. To remove the scaffold, the team applied pressure to the modules inside arches to minimize lateral movement as the OSB ribs were lowered from the centre moving to the footings. This sequence allowed the modules to shift and find their optimal position under gravity, ultimately ensuring a fully topologically interlocked and self-supporting structure (Figure 7).

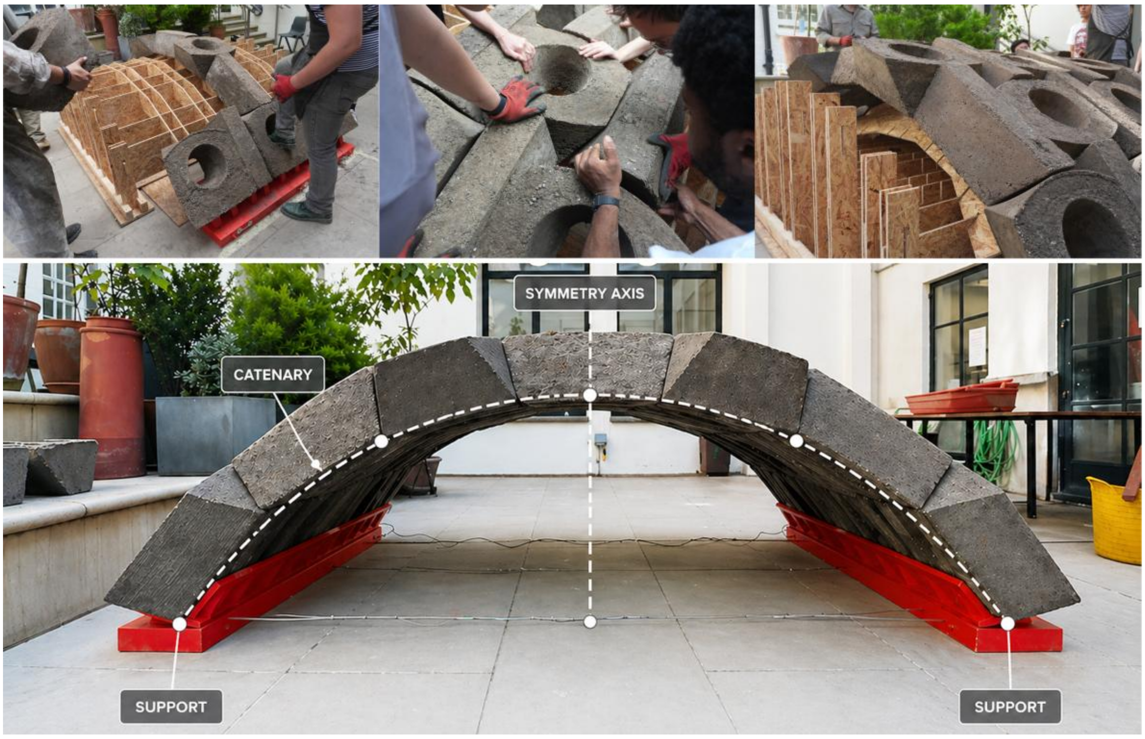


Figure 7. Step-by-step assembly sequence and the staged removal of the structural scaffolding to activate the interlocking mechanism.

## 4. Discussion and Conclusion

The successful realization of the 1:1 prototype validates the research hypothesis that a synergy between material computation and robotic fabrication can produce high-performance, demountable architectural interventions (Figure 8). The prototype highlights a fundamental shift from permanent, binder-heavy construction to a reversible, geometry-based logic. By utilizing a lightweight concrete mixture, the team achieved a density reduction of 50% compared to standard concrete. This material optimization was critical for managing the structural demands of the 700 kg+ assembly while maintaining the necessary compression strength for the osteomorphic interlocking modules. These sustainability claims are supported by concrete quantitative metrics across three areas: waste reduction, mass optimization, and lifecycle reusability. First, the geometric rationalization of the assembly from 10 unique modules down to 4 yielded a 60% reduction in required mold variations. Instead of generating substantial single-use timber or foam waste typical of subtractive CNC fabrication, the project required printing only 4 reusable PLA molds, each operating at a high-efficiency rate of three casting cycles per day. Second, replacing standard gravel and sand with local soil and lightweight perlite reduced the structural dead load by 50%, minimizing transportation energy and handling loads. Third, because global structural stability relies entirely on boundary friction and funicular geometry, the 700+ kg assembly is completely reversible, permitting a 100% material recovery rate at end-of-life without the downcycling typical of mortared masonry. A significant finding of the research is the discrepancy between idealized computational simulations and physical performance. While digital prototyping ensures mathematical accuracy, the manual nature of casting introduces deviations in weight and dimensional accuracy that can destabilize the system. The topologically interlocking system proved highly sensitive to these geometric tolerances; however, the use of a funicular catenary form effectively minimized bending stresses and ensured that the modules remained in a state of compression. The final assembly sequence confirmed that as the scaffolding was removed, the modules shifted and found their equilibrium positions, resulting in a self-supporting, interlocked structure. Furthermore, the robotic 3D-printing workflow for formworks provided a superior alternative to traditional subtractive manufacturing. The complexity of the interlocking faces would have required labor-intensive CNC milling and significant timber waste under traditional protocols. By rationalizing the 35 components into four unique module categories, the research minimized material consumption and casting time. The use of reusable PLA moulds not only reduced construction waste but also established an economically viable path for the production of bespoke architectural components. This research demonstrates that Topologically Interlocking Assemblies (TIAs) provide a resilient strategy for sustainable construction by enabling the creation of binder-less, reversible structures. Although the system demands high precision in both the component fabrication and global assembly phases, the integration of advanced computational tools and robotic fabrication allows for these ancient structural principles to be applied in a contemporary architectural context. The project successfully transitioned the built environment from a source of waste to a temporary material bank where structural components can be recovered, recycled, or reused. The results establish a new design paradigm where material efficiency, optimization, and robotic precision converge. Future work will focus on two primary lines of inquiry: the exploration of different concrete mixes to further offset the carbon footprint and the application of these interlocking principles to more complex, doubly curved surfaces. Ultimately, this research provides a framework for demountable interventions that challenge conventional assumptions regarding the permanence and environmental cost of material realization.

Figure 8: Final Prototype, titled Morpho-Lock. Photos by Elena Andreea Teleaga

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