Porosity and Interlocking

Digital stereotomy for small-scale structures with irregular stone

Mengdi Mao[1], Marjan Colletti[2], Guan Lee[3]
[1,2,3]University College London
[1,2,3]{ucbvmm0|m.colletti|k.g.lee}@ucl.ac.uk

This paper explores the use of irregular small-scale pebbles in constructing dry-fit, topological interlocking structures through digital stereotomy. Rooted in the traditional elegance of masonry without fastening materials, the study builds on the shift from handcrafted stonework to computational design and subtractive fabrication. By leveraging advancements in CAD/CAM technologies and CNC milling, the research redefines digital stereotomy as a flexible, sustainable material system. Inspired by Abeille's Flat Vault, which employs repetitive tetrahedral geometries, the study introduces parametric porosity to minimize material waste while preserving interlock through varied contact surfaces. These porous configurations not only maintain structural integrity but also improve environmental performance by enabling airflow and light transmission. A custom algorithm processes nonstandard, 3D-scanned pebbles, generating interlocking geometries tailored to each stone's unique form. The design process begins with truncated tetrahedrons and adapts to available digital stone stocks, integrating structural analysis and optimization based on mesh data. This approach addresses sustainability in construction by giving natural stones a renewed lifecycle through precise, efficient fabrication. Ultimately, the study positions digital stereotomy as a bridge between natural material aesthetics and advanced structural functionality, offering innovative potentials for small-scale architectural applications.

Keywords: *Subtractive Manufacturing, CNC Milling, Topological Interlocking Assembly, Dry-fit Masonry, Stereotomy, Irregular Stone, Porosity.*

INTRODUCTION

Construction and demolition waste accounts for approximately one-third of all waste generated in the European Union (European Commission, 2020). To reduce the environmental impact of construction, two key opportunities should be considered. Firstly, using natural building elements for structural applications offers distinct advantages. Steel and reinforced concrete are the primary emission sources, accounting for almost 66% of total building material emissions (Zhong et al., 2021). In contrast, stone has a relatively lower carbon footprint (237kg/m3) compared to clay brick (345kg/ m3), reinforced concrete (635kg/m3) and steel (12090kg/ m3) (Pliteq Inc, 2022). This makes stone a decent material for architectural construction, particularly considering its low embodied carbon, durability, and natural cooling properties. Secondly, porosity plays a crucial role in contemporary masonry structures. With the aid of digital technology, architectural

porosity offers new possibilities such as reducing material usage.

Typically, natural stone intended for use has irregular and nonstandard dimensions and may require a cutting process, which is related to the term "stereotomy". This term first appeared in architectural literature in 1644, in *Jacques Curabelle's Examen des oeuvres du Sieur Desargues*. As a fabrication technique, stereotomy (Greek: stereós "solid" and tomē "cut") originated in the Gothic period and involves stone blocks that are cut into discrete ashlars with specific shapes (Miodragovic Vella and Kotnik, 2017). The practice of cutting solids and aggregate blocks into structures has been established since ancient times.

Historically, the stone cutting involved in masonry architecture required skilled stonemasons proficient in structural and geometric analysis of architectural shapes (Figure 1). The construction process involves stone cutting and onsite stone laying, both of which rely on the traditional handicraft skills of stonemasons. Thus, "crafting by hand" serves as a quasi "interface" between the technical constructive possibilities inherent in the material and the skilled treatment and interpretation by the stonemasons (Carpo, 2012). Nevertheless, stereotomy was laborious and required a mastery of intricate procedural drawings known as traits, which served as cutting instructions. Thus, using basic identical bricks and mortar to compensate for tolerances proved to be more appropriate for the construction sites and unskilled workers during that period.

Later In the twentieth century, stone masonry was nearly forgotten, leading to a decline in stereotomy. The main reason for this decline was a shift in architecture that emphasized economic efficiency in design and construction to facilitate mass production. To achieve this, standard and repeatable materials like steel and concrete were introduced into the design and fabrication process.

Figure 1
Crafting Bath stone by hand

Consequently, classic stereotomy which was more labor-intensive and needed a deep understanding of complex structural forms began to show signs of decline.

Whereas in the past, stone was cut manually using hand tools, today this process can be fully automated by computer-guided cutters. McCullough suggests that, with computers as a medium, there is motivation to investigate the possibility of craft within the emerging realm of information technology, emphasizing the close relationship between them (McCullough, 1996). In McCullough's argument, the designers' activities in using computers with their hands and brains are likened to craftsmen's with their hands and tactile experience. As a result, digital craft mediates the relationship between humans and materials through computational intervention, extending stereotomy beyond its traditional techniques. Unlike conventional stone architecture, where design and manufacture were separate processes, innovative approaches now directly integrate design data into the fabrication workflow. The integration of digital workflows also enables the creation of more complex geometries, expanding beyond the geometric constraints of traditional stereotomic design.

Stereotomy emerged at the intersection of multiple fields, such as mathematical geometry, architecture and structural theory. An example of

non-standard stone used for dry assembly is architect and engineer Joseph Abeille's Flat Vault. The innovative stereotomy is an exception, which forms a load-bearing stone floor. A precise comprehension of geometry is essential for understanding masonry (Heyman, 1995). Thus, it is meaningful to explore the intrinsic block relationships within the interlocking masonry structures discussed below. Identical truncated tetrahedron-shaped stones were arranged in a 2D woven pattern that spanned the vault, without the use of a keystone or mortar (Tessmann and Becker, 2013). The Topological Interlocking Assembly (TIA) is a modern extension of Abeille's Flat Vault and is defined as a material system. It refers to an assembly technique, derived from stereotomy, in which internal elements are locked both translationally and rotationally (Dyskin et al., 2003).

Apart from recent studies on the geometry and materiality of TIA, contemporary projects like Stone Matters by AAU Anastas aim to merge innovative parametric design and computational simulation with local traditional stereotomy. The Cyclopean Masonry combines ancient construction techniques with advanced digital processes, advocating material cannibalism as a strategy to combat excessive construction waste (Clifford, McGee and Muhonen, 2018). In general, the application of TIA in architecture has the potential to transform design and fabrication processes by enabling efficient assembly and disassembly methods. This research aims to learn from the craft of traditional masonry while tracing its evolution toward digital stereotomy. It seeks to address the following questions:

- Can digital stereotomy enhance crafting and transform stone into structurally sound structures?
- Can topological interlocking assemblies serve as a technique to aggregate irregular small-scale stones into dry-fit porous structures that also allow for easy assembly and disassembly?

METHODOLOGY

As previous designs have illustrated how the geometric principles underlying TIA facilitate a more comprehensive understanding of the interactions among 3D-printed blocks (Mao, Colletti and Lee, 2024). To answer the research questions, this research methodology focuses on the material and design practices involved in using irregular stone to construct topological interlocking structures. The workflow can be divided into six steps:

1. scanning and digital pebble library,
2. generating porous topological interlocking assemblies,
3. stone matching,
4. structural optimization,
5. subtractive manufacturing,
6. and assembly sequence.

Pebbles were selected as the primary material for the small-scale experiment. This design strategy respects the inherent characteristics of material by allowing pebbles to retain parts of their original shapes. By emphasizing their natural beauty and integrity, these pebbles are transformed into elements of a new TIA.

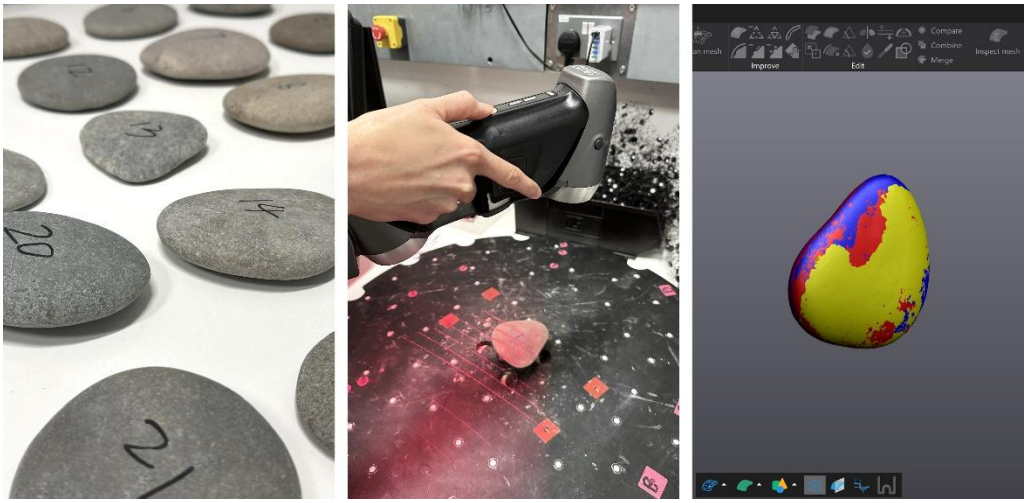


Figure 2
3D scanning of pebbles using the Creaform Handy Scan 700

Scanning and digital pebble library

Standard materials like steel and concrete are typically accessible to designers through online catalogues with labelled dimensions and appearance. However, natural nonstandard materials intended for future fabrication require 3D scanning to accurately capture their random geometries, allowing these virtual models to be collected into a digital inventory. Unlike a human surveyor, the scanning process records an object in its current state, including details such as texture and color (Norell, Rodhe and Hedlund, 2021). For small-scale pebbles used in this research, Creaform Handy Scan 700 which is a handheld structured laser scanner is chosen based on the size of material (Figure 2).

The first step of the digital workflow is to thoroughly survey and document pebbles. 27 pebbles were numbered with marks and individually laser-scanned, with each pebble captured 4 times by the scanner to fully record its geometry. Every set of 4 scans was then merged into a single, clean mesh using VXElements software. The scanned pebbles were saved as digital mesh data and imported into Rhino Grasshopper (GH) for further analysis and characterization.

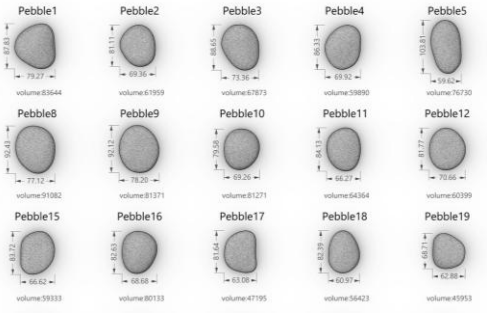


Figure 3
Selected digital pebble library

Settimi Andrea and his team from EPFL presented Cockroach plugin using a Rhino and GH interface (Settimi et al., 2022). It's a point cloud post-processing tool built on C++ capable of efficiently modelling irregular objects from LiDAR scans. This high-level point cloud tool is valuable for using nonstandard stones to create a sustainable building environment.

The 27 mesh geometries were down sampled by reducing the point cloud data by 50% while preserving as much of the original global form as possible, thus enabling a more efficient digital modeling workflow. In addition to the simplified mesh data, the virtual irregular pebble library records detailed information, including the name, size, edges, volume and bounding-box dimensions of each pebble (Figure 3).

Generating porous topological interlocking assemblies

Using geometric software as an interface can bridge the stages of design and fabrication, demonstrating robust interaction capabilities that enable a seamlessly transition from 2D patterns to 3D aggregation methods. The generation workflow consists of four steps: (1) inputting 2D grid data, (2) constructing perpendicular planes, (3) rotating planes, and (4) truncating tetrahedra. Building on previous studies inspired by Abeille's Flat Vault, which typically consists of repetitive tetrahedrons arranged into a closed, non-porous floor or roof, this design introduces parametric variations in porosity.

Considering the general shape of the scanned pebbles in the digital library, a 2D square-based grid was introduced and scaled into discrete rectangles. Subsequently, four perpendicular planes were constructed from the edges of each rectangle. These planes were then tilted either toward or outward from the rectangle's center by an angle α. Consequently, the intersection points of the four planes generate a tetrahedron integrated within the interlocking grid structure. To create slab-like geometries, the tetrahedra were truncated by two offset surfaces positioned at equal distances on either side of the reference rectangles. This workflow enables easy adjustment of the base grid size, plane rotation angle, and module thickness, resulting in parametric variations in the gaps between blocks. These variations reduce the amount of irregular stone material that requires milling, while preserving the interlocking mechanism through variable contact surfaces between blocks. Architectural porosity thus reduces material waste, ensures structural stability and allows controlled variations in light and airflow.

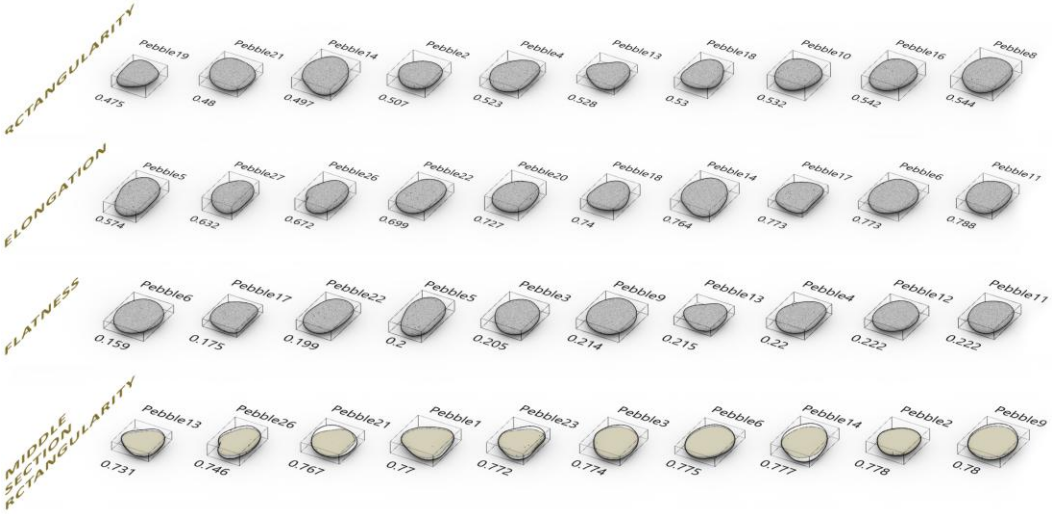


Figure 4
Stone characterization example

Stone matching

Beyond basic properties such as name, size, volume, and bounding box, many of these description focus on the pebble's geometric form rather than its scale. These include measures such as rectangularity, elongation, flatness, and middle-section rectangularity (Figure 4). These factors are visually characterized as reference in stone matching process, which begins with truncated tetrahedra.

This design approach takes into account the specific geometric characteristics of the digitally stocked material. Out of 27 pebbles, 24 with relatively regular shapes were selected to form a four-by-six block TIA. Interlocking blocks were then divided into three groups: four corner modules, twelve boundary modules, and eight inner modules. The 24 scanned meshes were aligned with the target interlocking geometries based on their characteristics. These virtual stones overlapped and were then carved at the intersections. For the four corner modules, the top and bottom shapes of the pebbles were preserved, with only two sides requiring machining. The twelve boundary blocks required machining on three sides, while all four sides of the eight inner blocks were machined. The whole process were visually simulated in Rhino GH environment. This algorithm manipulates stone geometries into the pre-designed porous TIA to minimize the amount of carved-away material (Figure 5).

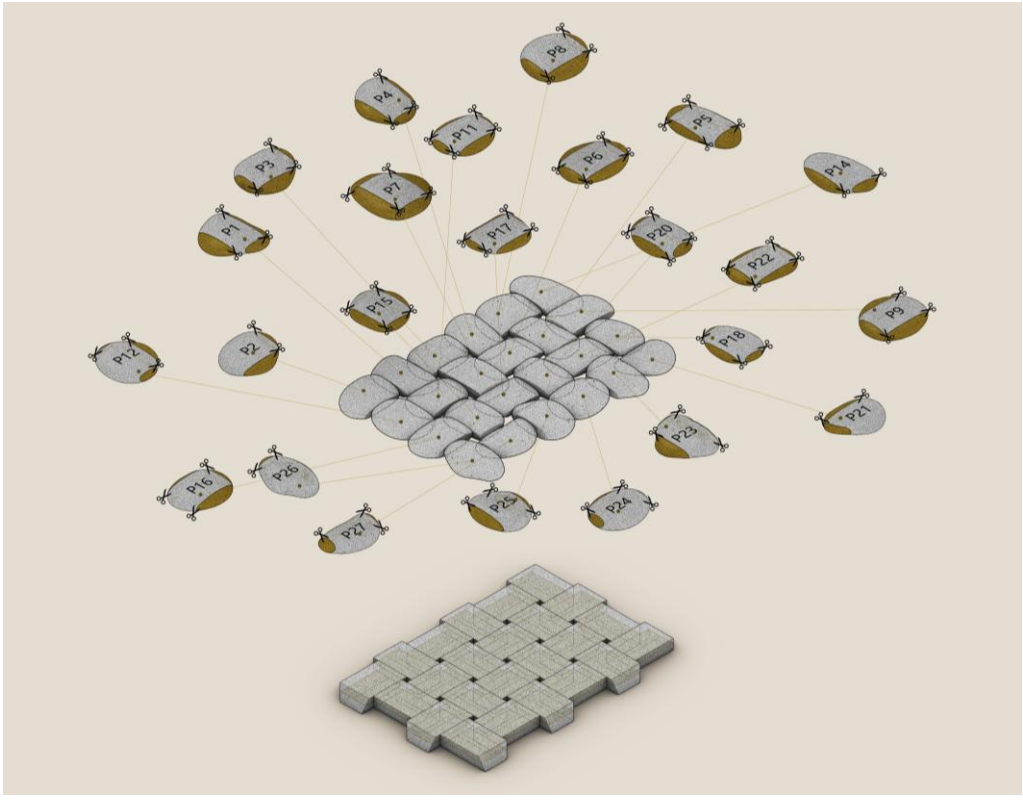


Figure 5
Stone matching

Structural Optimization

Alongside the stone matching process, structural optimization was conducted based on the design iterations, utilizing information collected from the stone mesh geometries. The optimization process ensures that the subsequent assembly is both geometrically feasible and physically stable. Unlike conventional optimization algorithms that simulate geometries within predefined boundary conditions, this process uses the tilted planes of the target truncated tetrahedron to split the material. The contact surfaces between aligned pebbles vary depending on the optimized alignment angles and the properties of the interlocking blocks. The size of the cutting tetrahedron was ultimately determined by the average dimensions of the scanned meshes, and the tilting plane angles were set at 15 degrees for the subsequent manufacturing process.

Subtractive manufacturing

During the exploration of integrating natural material into new structures, fabrication processes can be divided into two parts: stone cutting and stone laying. Subtractive methods, which involve cutting and carving stone, have evolved since Neolithic times. The advancements in mechanistic operations brought about by industrialization have further refined these subtractive processes (Fernando, 2019). Recent advancements in Computer-Aided Design and Manufacturing technologies have significantly improved the precision and efficiency of digital stereotomy, enabling the advanced fabrication of interlocking geometries through CNC milling techniques.

Maintaining stability during machining is challenging due to the hardness of the material. Given the small size of the pebbles, they were milled using a 3-axis CNC machine in combination with a pre-fabricated work holding system. This system consists of two parts: sandwich structures to secure pebbles and milled baseplates to anchor the sandwich structures. Wood originally used for packaging was reused, milled to precisely fit the scanned geometries of pebbles (Figure 6a). The top and bottom work holding pieces were numbered and aligned with the corresponding names of the 24 pebbles (Figure 6b).

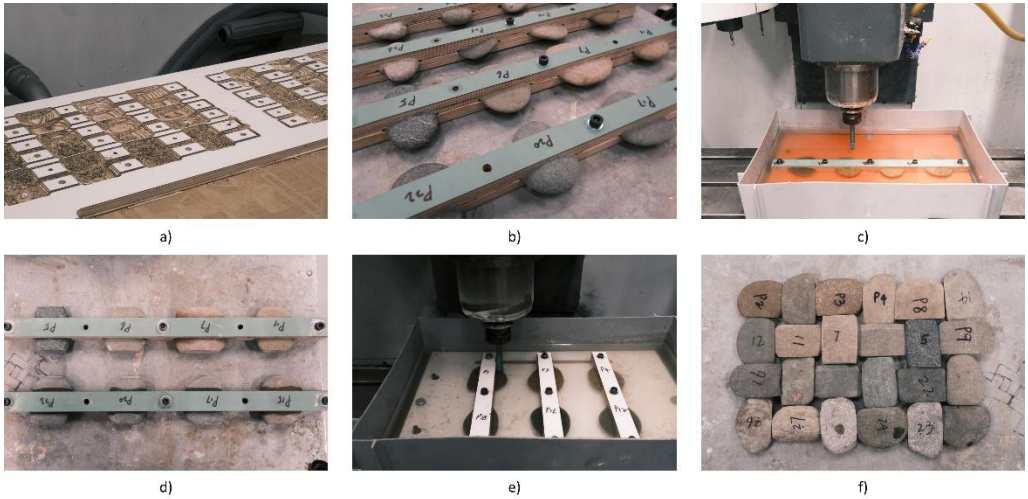
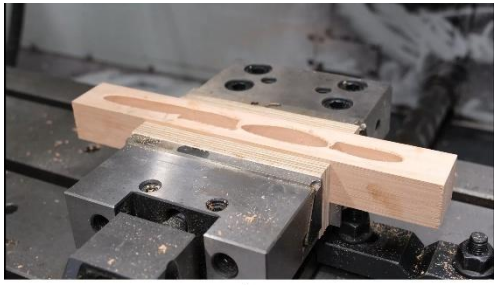


Figure 6
Subtractive manufacturing
a) milling work holding for pebbles, b) sandwich structures, c) first operation, d) milling outcome, e) second operation, f) final outcome

A water-filled box was prepared to suppress silica dust during milling (Figure 6c). The sandwich structures were secured to the baseplates within the box prior to machining. Given the size of the box, every four pebbles were grouped together for the initial operation, which involved machining one set of two parallel edges (Figure 6d). The entire subtractive manufacturing toolpath was designed using Fusion360 software. The pebbles fit precisely within the sandwich work holding system and were milled at a 15-degree angle. A similar strategy was employed to mill the second set of parallel edges, with six pebbles grouped together (Figure 6e, f).



a)

b)

Figure 7
Assembly sequence
a) milling frame,
b) additional tie-down strap

Assembly sequence

Since topological interlocking does not apply to the boundary modules, a fixed boundary is required. A wooden boundary frame was milled to allow partial insertion of the uncut edges of outer sixteen pebbles. In the stone assembly phase, since TIA is mortar-free and relies on the precise placement of each block, it has to be pre-simulated to ensure accurate positioning of all pebbles. Additional lifting techniques need to be used during assembly. Additional lifting techniques were required during assembly. Instead of a prefabricated formwork, a sand-filled box was used, offering greater flexibility and sustainability. The assembly sequence began by placing the eight inner pebbles onto the sand, corresponding to the names specified in the pre-simulated GH file. The outer inserted pebbles were then aligned with the inner blocks and secured using an additional tie-down strap until the overall structure became stable. The final pebble assembly achieved interlocking in both vertical and horizontal directions (Figure 8). The dry-fit prototype can be assembled by unskilled laborers using reference guides for stone positioning.

DISCUSSION

This comprehensive design-to-fabrication workflow enables the construction of planar masonry geometries using natural pebbles. The final output is a table sculpture measuring 395 mm × 270 mm × 250 mm. By reducing cutting waste through stone matching to a porous target geometry, the process utilizes 82% of the material from the 24 scanned pebbles. The design methods demonstrated in this research have the potential to generate structures ranging from small-scale sculptures to large-scale building envelopes.

Further steps can be explored to improve this design. Firstly, the 3D scanning of these small-sized geometries recorded only mesh data, without capturing texture or color. These aspects could be explored in future scaled-up research using FARO LiDAR scanners or photogrammetry techniques. Secondly, although a sandbox formwork is more sustainable and readily available, it slightly reduces the accuracy of the interlocking structure. Thirdly, a comparison between the milled geometries in the pre-simulated digital environment and the physical outcome presents an area for further exploration. Lastly, exploring a more flexible boundary condition to replace the tie-down strap could further enhance the assembly system. In this design, the pebbles are

assembled by hand. In future work, I will investigate large-scale building envelopes including roofs and facades constructed from structural stone that can be machined and assembled using robotic systems. This approach not only promotes a sustainable architectural environment but also enables the creative incorporation of nonstandard material into new constructions.

Figure 8
Final interlocking table

CONCLUSION

This research utilizes 3D scanning and CNC milling techniques to transform irregularly shaped pebbles into topological interlocking geometries, drawing inspiration from historical precedents such as Abeille's Flat Vault. These technologies offer significantly greater precision and control compared to traditional handcrafting methods. Through parametric modelling, architectural porosity is introduced to reduce material waste and enhance airflow and light transmission, with potential for application in scaled-up designs.

This research shows how TIA addresses contemporary environmental challenges in sustainability by utilizing nonstandard building materials and reducing reliance on carbon-intensive systems such as steel and concrete. The outcomes of this work highlight the architectural potential of porous and interlocking assemblies and demonstrates the value of combining material intelligence with digital advancements.

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