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A new type of interlocking stone structures : bridging high-tech design and low-tech manufacturing

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Abstract

With sophisticated digital tools, design approaches have evolved, giving rise to innovative constructive practices despite multiple and significant constraints like manual manufacturing, raw material usage, and intricate morphologies. This article introduces a high-tech design process tailored to low-tech manufacturing, applied to a stone structure comprising mixed materials—cut stone and plaster. The structural design principle originates from Joseph Abeille's interlocking concept, facilitating the generation of a stone structure with low peripheral thrusts, emphasizing bending stress on individual stone blocks, and enabling centring-free manufacturing mainly guided by block contact surfaces.

To explore a broad morphological space, a key variation from Abeille's concept involves generating contact joints using "Triply Orthogonal Systems of Surfaces (TOS)". This new implementation rationalizes local block generation based on precise geometric constraints imposed by the soft limestone material's structural capacities, especially on block edges. The dynamic and interactive exploration of the structure's overall morphology, including surfaces with negative Gaussian curvature, is achieved through a geometrically constrained parametric design process. Not only does this process allow wide design space exploration, but it also ensures coherence among other rationalization constraints and parameters. Addressing complex questions during the preliminary design phase made it possible to establish the conditions for the simple and rapid manufacturing of a partial prototype of an interlocking hand-cut stone vault executed in four days by architecture students with stonemasonry trainees.

Keywords: Interlocking stone structure, Triply Orthogonal Systems of Surfaces (TOS), High-Tech design, Low-Tech manufacturing, Fabrication-aware design, Centring-free assembly, Stereotomy

1. Introduction

1.1. State of the art

In the evolving landscape of architectural design and construction, the advent of digital technologies has fostered a significant shift towards integrating innovative methodologies. This transformation is particularly relevant in the domain of stone masonry and construction, where the historical art of shaping and assembling stone structures meets contemporary design and fabrication processes. The exploration of topological interlocking systems exemplifies this shift, merging sophisticated design processes with practical, low-tech manufacturing techniques.

Stone masonry, rooted in historical significance and architectural heritage, offers unique challenges and opportunities for modern construction. Its high compression resistance countered by limitations under tension, low environmental footprint, and thermal efficiency align seamlessly with the increasing emphasis on eco-friendly construction materials. Despite these advantages, challenges persist in the widespread adoption of stone within modern construction. Issues such as an outdated industry, technical

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constraints, and elevated costs impede its broad utilization, necessitating innovative solutions for the seamless integration of stone into contemporary architecture. Topological interlocking systems introduce a groundbreaking approach to stone construction, enabling complex structures that leverage the stone's natural strengths while addressing its weaknesses [1].

Dyskin et al.'s contributions have been pivotal in establishing the theoretical foundations and practical applications of topological interlocking, exploring its geometric properties and proposing its viability for building in extraterrestrial environments and modern construction [2], [3]. Many scholar's research in this area have adapted interlocking principles to contemporary challenges, such as mitigating static response to thrust forces in vault constructions [4], [5], [6], [7]. Further contributions by Kurucu, İlerisoy, Tosseman and Loing extend topological interlocking applications in architectural design, offering innovative solutions to traditional construction challenges and redefining stone masonry's possibilities in contemporary architecture [8], [9], [10]. Significant inquiry has centered on topological interlocking assemblies for architectural constructions, emphasizing structural advantages from kinematically constrained elements [11]. Those works highlight a transition towards adaptable and resilient architectural forms, capable of withstanding stresses through intelligently designed block interconnectivity.

The GSA's focus on cut stone structures, led by Maurizio Brocato, has explored interlocking concepts to optimize stress distribution, reduce peripheral thrusts, and promote sustainable manufacturing processes [1], [12], [13], [14]. These studies highlight the importance of early-stage fabrication and parametric design in ensuring structural integrity and facilitating morphological exploration within stone construction.

1.2. Objective

This research aims to develop digital tools, and facilitate the assembly of complex structures without traditional centering, relying instead on precise block arrangements and contact surfaces based on block-based structures using Triply Orthogonal Systems of Surfaces [15]. This methodological shift emphasizes aesthetic appeal and structural integrity, heralding a new paradigm in stone construction.

This body of research aligns design innovation with practical, low-tech manufacturing, addressing stone's challenges and advocating for economic and sustainable fabrication techniques. It reflects a concerted effort to harness stone masonry's potential in creating innovative, resilient, and environmentally conscious designs. This effort not only advances architectural design but also supports broader sustainability goals, advocating efficient material use and innovative practices amidst global environmental challenges.

2. Theoretical principles for conception

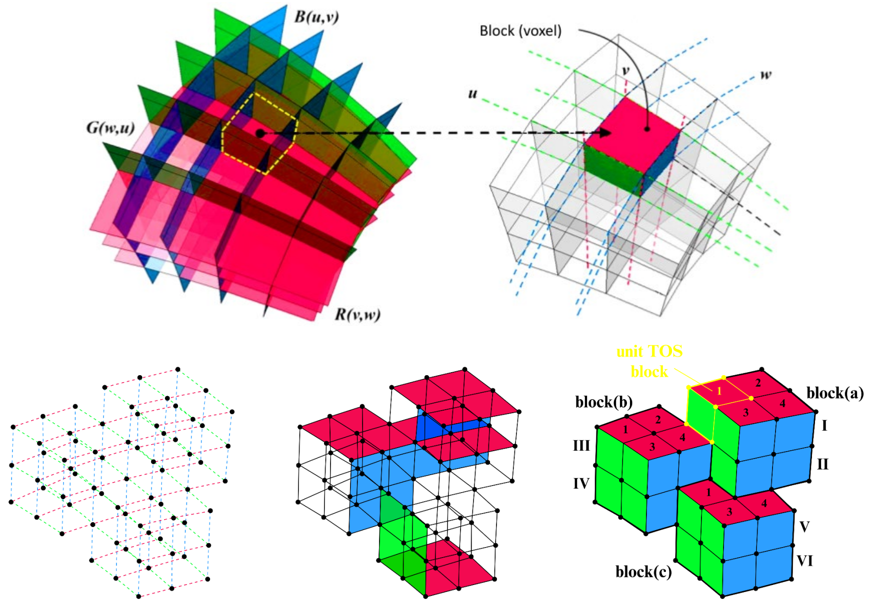
The motivation behind the design method is to allow the integration of construction-related considerations in the design process from the onset. This integration is made possible by mobilizing through parametric formulation the geometric properties of mathematical surfaces or systems to address those considerations. This approach allows us to revisit, revitalize, and revalorize traditional/historical (low-tech) construction methods by expanding their applicability to forms or shapes that go beyond -in terms of their level of complexity- the ones they've historically been associated with.

The design process therefore ensures the exploration of reciprocal structures whose elements are mainly subject to bending, following specific geometric rules which result from previous mechanical study of reciprocal structures of the same type, although more standard [12]. A future development may consist of quantifying the mechanical bending stresses generated in these new more complex systems, and the integration of these structural considerations in the design process.

2.1. Interlocking masonry with Triply Orthogonal System (TOS) of surfaces

The design approach employed attempts to demonstrate how mobilizing relevant geometric entities (surfaces, patches, and transformations) such as the Triply orthogonal system of surfaces (TOS) is used to achieve low-tech construction of performative structures.

As explained in [15] (co-written and developed by the authors of this article), two levels of design parameters are given to the designer to select, modify, transform, and rationalize said TOS. First, the global level, where the shape of the structure is determined through selection, modification by manipulating the variables in the mathematical equation, and transformation by manipulating the variables in a 5x5 matrix that applies a Mobius transformation which create a space of morphological possibilities without losing any geometric properties of the TOS. Second, the local level, where the structure is subdivided by manipulating the parameter space which varies the proportions of the blocks and rationalized by capitalizing on the geometric properties of principal curvature parameterization which allows the designer to define the nature of the blocks faces (flat, developable, or doubly curved). In the same article, a potential method to reinterpret and integrate Abeille's interlocking bond to the 3D array of the TOS system block system.



The 3d array of points generated from the intersection of the u,v,w curves

Specific points of the 3d array of points are connected by lines to create planar faces

The stepped selection of the unit TOS blocks allows for the interlocking assembly. Each big TOS block is made out of 8 unit TOS blocks

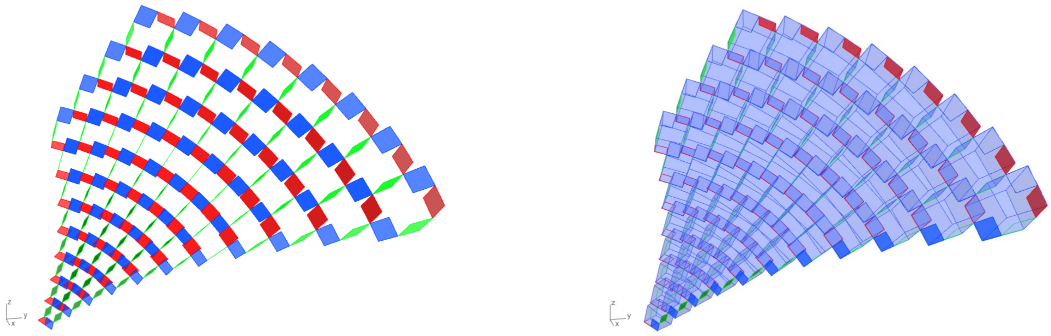
Figure 1: Generation of the TOS vertices arrays defining the initial interlocking system [15]

In the following we specify how through supplementary parameters we were able to address construction and mechanical concerns.

2.2. Optimization of fabrication features using TOS properties

2.2.1. Portion extraction

Generally, mathematical surfaces are bound by two domains (u,v), as in the case of the TOS, since it’s a triple system, by 3 domains (u,v,w). Parametrically attributing upper and lower bound values to those domains allows us to extract a specific portion of that system to be further detailed (figure 2). Through this parametric setup, that presents not only a method of morphological exploration, but also a way to “find” a portion of the system that addresses certain project/site constraints. In the case of our structure and given the objectives and boundaries of our experimentation, we’ve chosen to find a portion of the system (i) that would globally have a negative Gaussian curvature and (ii) locally have blocks of the same scale of dimension. The criterion (i) was motivated by exploring Abeille’s interlocking system applied to a non-standard negatively curved shape, while the (ii) was motivated by reducing material waste and the overall cost since most of the final blocks could be cut from the same kind of standard size stone.

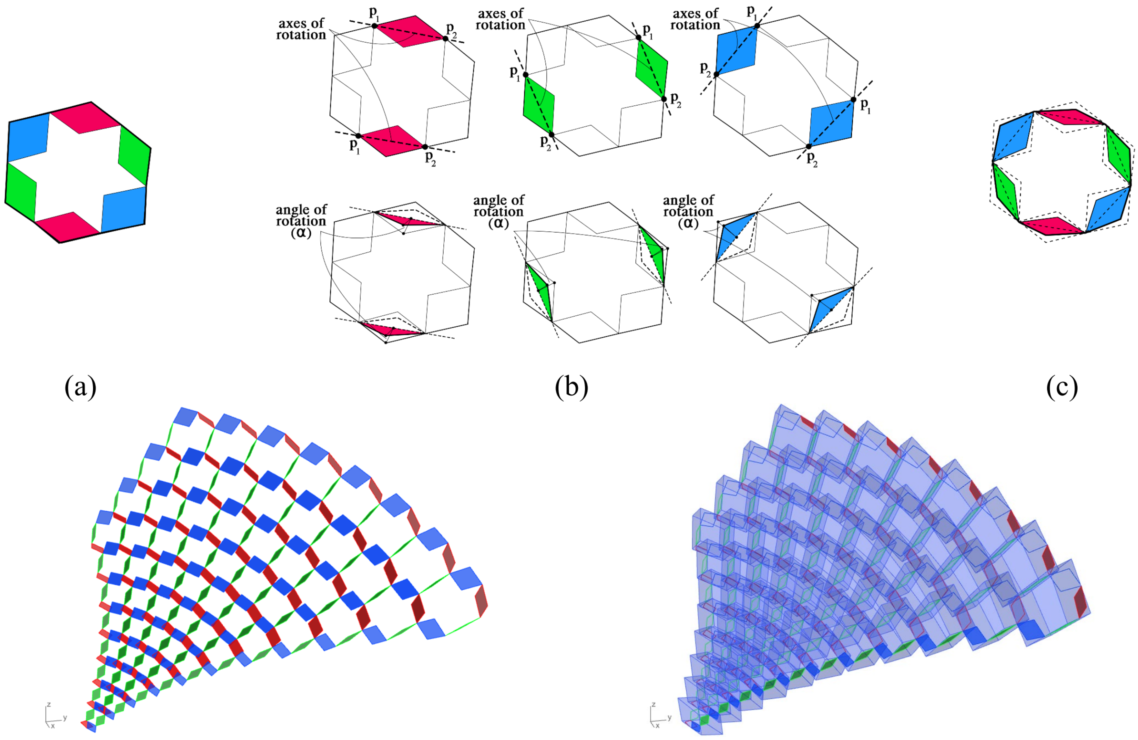


(a) (b)

Figure 2: (a) Initial contact surfaces of the selected TOS boundaries, (b) associated interlocking system with initial cuboids in light blue

2.2.2. Joint rotation

As explained in 2.1., the TOS interlocking system is based on a system of cuboids (6 plane volumes with dihedral angles close to 90°). Thus, by default, it generates an interlocking system with joint angles close to 45°, relatively to the global surface. While it is necessary to decrease this angle to avoid fragilities in the stone (caused by acute angles), it is important nonetheless to avoid decreasing the angles to the point where the structure starts behaving as a flat vault with straight joints. As shown in [12], a compromise would be to rotate the joint surfaces with an angle of 15° in order to obtain an interlocking angle of 30° instead of 45°. As shown in figure 3, the geometric construction of the TOS is particularly useful since it allows performing such rotation (about each face's diagonal axis) directly through its parametric definition without losing its geometric properties. In doing so, the need for specific algorithms to ensure the optimal 30° joints angle at each contact surfaces becomes obsolete.



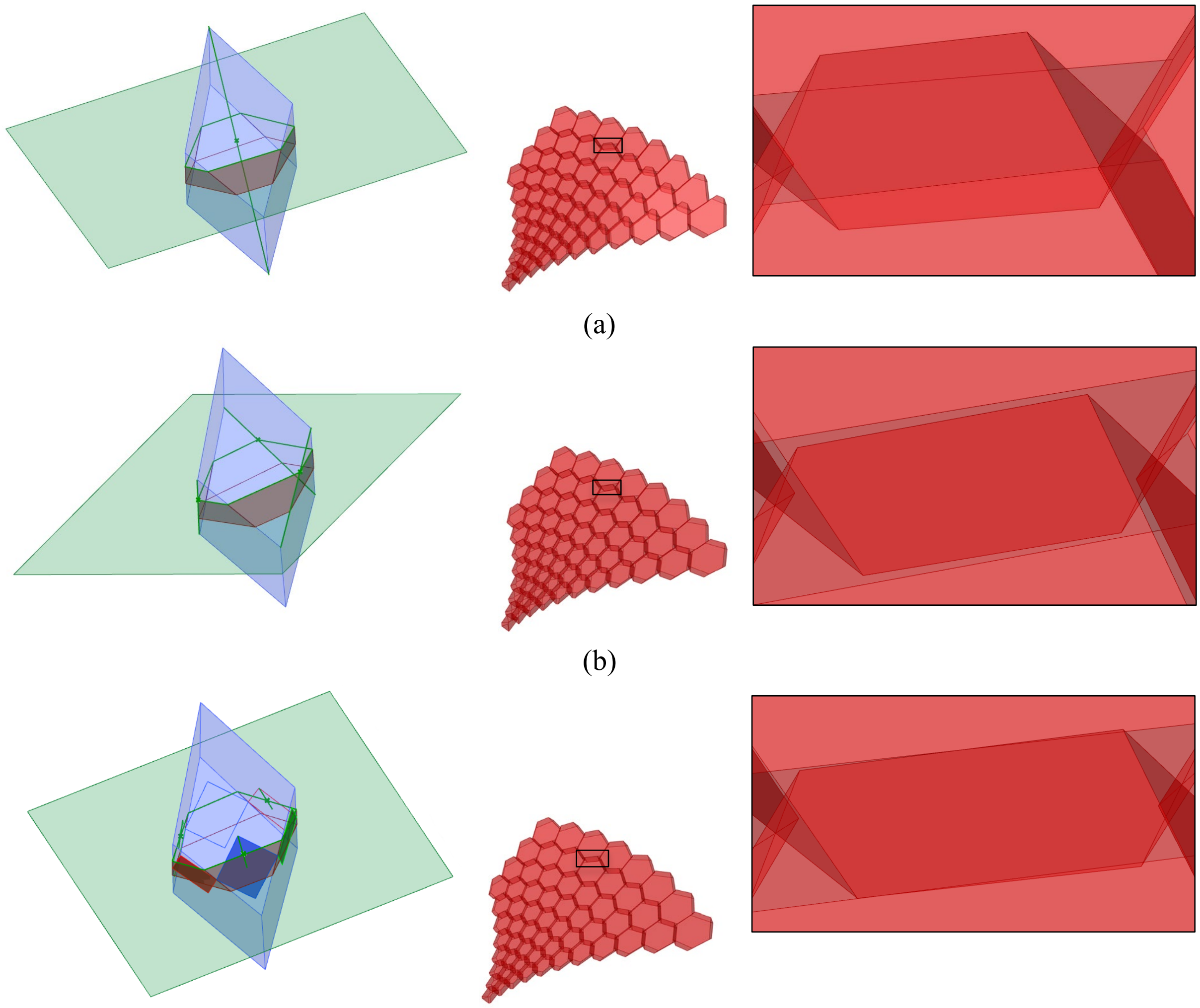
(a) (b) (c)

(d) (e)

Figure 3: Rotation of the contact surfaces ; (a) initial contact surfaces of the interlocking system generated by the TOS, as shown in figure 2a, (b) rotation of each contact surfaces around axis passing through the two corner points by an angle α = 15°, (c) new contact surfaces of the final interlocking system, (d) rotated contact surfaces for the selected TOS boundaries, (e) resulting interlocking system with "modified" cuboids in light blue

2.2.3. Truncation planes

Cutting every "modified" interlocking system block with 2 parallel truncation planes of constant distance allows us to "standardize" the construction of the vault since having blocks of constant thickness greatly simplifies the stone extraction process at the quarry. It's also worth noting that the orientation of the truncation planes was determined so as to minimize local discontinuities and obtain intrados/extrados surfaces which are, to a great extent, visually continuous. As shown in figure 4, the final selection of the truncation plane is chosen among different possibilities : constructions in figure 4a (using a plane perpendicular to the diagonal of the light blue "modified" cuboid after the contact surfaces rotations) or in figure 4b (using a plane through 3 parametrized points on 3 opposed edges of the light blue "modified" cuboid after the contact surfaces rotations) generate a discontinuous global structure. On the other hand, by choosing a plane defined by 3 parametrized points which belong to the diagonals of the rotated contact surfaces, as shown in figure 4c, we can ensure a sufficiently smooth global surface. The other truncation plane is always parallel to this first plane, thus ensuring a constant thickness for all blocks.


(a)

(b)

(c)

Figure 4: (a) Truncation plane perpendicular to the diagonal of the light blue "modified" cuboid after the contact surfaces rotations, (b) truncation plane through 3 parametrized points on 3 opposed edges of the light blue "modified" cuboid after the contact surfaces rotations, (c) truncation plane through 3 parametrized points which belong to the diagonals of the rotated contact surfaces

3. Practical decisions for fabrication

During the week-long workshop, four days were dedicated to the intricate processes of carving and implementation. The collaborative team behind this project consisted of three mentors and 10 young students, comprising 5 architecture students and 5 stone carving students. Notably, stone carving is a novel experience for the architecture students. The fabrication process follows the main steps of the French stone carver from “Les Compagnons” : drawing, cutting, assembling (« Tracer, tailler, poser »).

The ultimate structure consists of 30 unique blocks, for a total weight of approximatively 500 kg. With tight transformation deadlines of approximately 2.5 days, including time for implementation, the project faces constraints in terms of human resources. Streamlining production becomes imperative, emphasizing the need for efficient organization. This presentation will delve into the tools employed to orchestrate the construction, followed by an exploration of the methods for drafting and carving. Concluding the discussion will be an overview of the installation process, providing insight into the final placement and arrangement.

3.1. Blocks scale decisions : «*Tracer, Tailler,…*»

In order to optimize production, conceptual tools are essential. One such tool is the simplified "Gantt chart," which helps identify crucial project stages and the critical path. We opted to have the entire team focus on carving the first two rows, followed by dividing the team, with one part dedicated to installation while the others continued the carving task. Templates significantly helped in organization and comprehension. Several visuals were prominently displayed, including an implantation plan, a diagram (listing each block), and a cutting sheet that validates different stages of carving progress. This ensures that each step, cutting, carving, third-party inspection, and implementation is completed. Every student thus knows which stone to carve and its destination within the structure. These construction tracking tools may seem commonplace, but it's crucial to maintain the project's primary educational focus and demonstrate the indispensable tools for a smooth project execution.

To streamline the ordering process from the quarry and reduce variables, we opted for a limited number of raw blocks, which are quarry-cut from 10 cm thick slices (figure 5a). Carving these blocks, composed of only 6 flat cuts, involves several steps. The initial stage is the site preparation, where the block is set on a support for marking and carving, requiring blocks manageable by two students. Given the nature of the stone, a visual inspection precedes the tapping or "sounding" of the block with a mallet to check for any internal cracks, indicated by a hollow sound. Subsequently, the exact height of the initial block is verified, and if it exceeds 10 cm, it is carved to the required thickness.

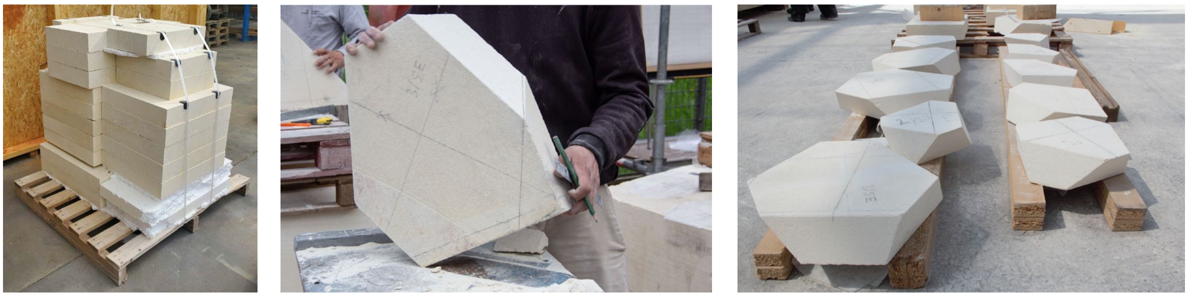
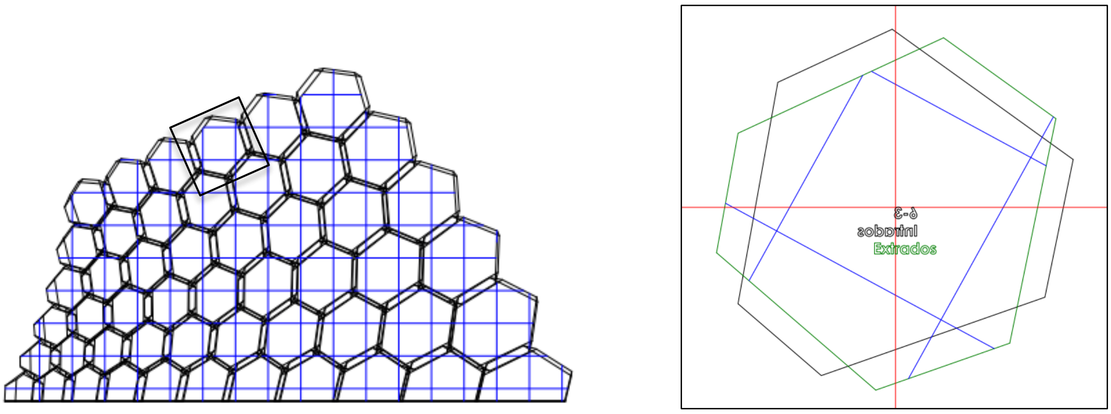

(a) (b) (c)

Figure 5: (a) Initial blocks slices delivered from the stone quarry with a thickness of 10 cm, (b) partially-cut stone block with 4 finished faces out of 6, (c) finished blocks

To trace the stone, we employ unique templates called "panels," individually tailored for each block (figure 6b). These panels are crafted from transparent plastic called "chablonite," printed, and manually cut. Certain crucial information must be included on each panel : the axes to position the panel relative to the initial block, as well as the stone's reference in connection with the diagram. Additionally, nomenclatures of adjacent stones are provided at joint locations (the contact surfaces between blocks).

Furthermore, we've chosen to use the same panel for both the intrados and extrados of the vault. To achieve this, we specify "Intrados" (black lines in figure 3b) and "Extrados" (green lines in figure 3b) on the panel, corresponding to the colors of the lines for "above" and "underneath." Since the panel is transparent, it's essential to read the word in the correct orientation, confirming that the panel is placed correctly.



(a) (b)

Figure 6: (a) View from the extrados with the level lines in blue, (b) panel for a block with extrados edges (in black), intrados edges (in green), panel axes (in red) and level lines (in blue)

The axes (red lines in figure 6b) serve to position the panel in a staggered manner between the intrados and extrados. In this carving method, the initial block must be precisely dimensioned, as the edges of the joint surfaces extend onto the block. The panel indicates these edges, guiding the carving process. If the initial block is too thick or too thin, the edges would no longer align with the extension of the surfaces.

Once the tracing is complete, the next step is to carve six flat faces while maintaining the specified angles (figure 5b). Manual tools such as chisels, a chasing hammer, a straight chisel, and a Zag (stone saw) are used in the process. The carving begins with "percussion tools" for rough work, including chisels and claws, where a mallet is struck on the tool handle. A first Zag cut removes a significant material quantity. Following rough work, a chiseling step establishes an initial reference plane, that extends from an edge and is approximately 2 cm wide, using "finishing tools" like the straight chisel. Two edges are then followed to create a plane.

Throughout the process, measurement and angle control tools such as rulers and squares are employed. It's crucial to verify the flatness of the faces by creating a St. Andrew's cross, placing the ruler from one corner to the opposite and ensuring it forms a straight line. This check is repeated for the other two corners to confirm the plane is not skewed. For the final plane finish, abrasive tools like the French drag (blades set in a wooden block) are used. Depending on the faces, it may be more efficient to use the zag, for cutting in softer stone. The finished blocks are stored near to the implantation place (figure 5c).

3.2. Structure scale decisions : «…*Poser* »

The free-centering assembly of the structure is carried out in a wall configuration. The design of the structure has been defined so that the stability of the structure can be ensured in this provisional configuration (in particular by the definition of the first row). Following assembly, the structure is flipped into its final horizontal position, like a slab, so as to work mainly in flexion, which is the principal feature ensured by its reciprocal definition.

A traditional flat wall features horizontal courses (rows of stones) that are level and in plumb. The lower part of the block is called the bottom bed, while the upper part is the top bed. However, in this particular case, the nomenclature of "bed of waiting" and "bed of installation" is retained. The wall lacks level courses and does not have a clear plumb reference plane (figure 7). Each stone within a course has multiple joint planes, and these planes are not level. This presents challenges in determining the precise spatial location of the stone for proper implementation, ensuring it can support its own weight.

Unlike a traditional vault where the formwork provides the reference and supports the stones during assembly, the TOS wall requires a different approach. The initial step in the installation involves mapping the beds of installation of the first course on a full-scale template (drawn to scale 1/1) on the floor, which has been previously printed. To position the blocks in space, references are essential. To address this, a grid is projected onto the wall (figure 6a). This grid involves tracing a vertical axis (ensuring plumb) and a horizontal axis (ensuring level) on the extrados. These axes are pre-marked on the blocks using transparent panels (blue lines in figure 6b), providing an additional guide for positioning the blocks correctly. A laser is used to ensure the axes are adhered to, though this system does not account for out-of-plane rotation of the wall. To address this, a solution involves marking the position of the bed of installation of the following block on the bed of waiting. The assembly is then carried out block by block, utilizing self-locking mechanisms to accommodate three waiting joints for correctly placing most of the blocks (figure 7a).


(a) (b)

Figure 7: (a) Structure during assembly with plaster and fibers in the joints, (b) preparation of the groove which was filled with fiber and plaster to retain the peripherical blocks

The installation is carried out using plaster and hemp fiber in the joints. This technique ensures the secure fixation of the stone in its final position, preventing the risk of tilting in the future, and has a relatively quick setting time. Additionally, the plaster contributes to strengthening the overall structure by providing significant tensile strength in the joints.

To create a peripheral binding, a continuous application of plaster and hemp fiber was chosen. A groove was made with an angle grinder in the perimeter blocks to accommodate long strands of plaster and hemp fiber. Furthermore, to enhance the overall structure's solidity, a rough plaster coating of approximately 1 cm, without hemp fiber, was applied to the extrados.

Figure 8: Flipping sequence of the final structure

To proceed with the turning and final placement, several steps are involved. Firstly, a formwork is created and placed on the intrados. This formwork consists of two panels positioned in parallel and connected. On the extrados, a central beam (chevron) is installed at the level of the structure centroid, supported by a plaster counterform (figure 8). The chevron is connected to the panels by three threaded rods that pass through the vault. Two slings are then placed at the ends of the chevron, acting as a beam. The flipping process is executed using a bridge crane (figure 8).

Once flipped 90°, the final placement is done on three support points, chosen somewhat arbitrarily to avoid excessive flexion in the structure. This means they are spaced adequately apart, without being located at the edges (figure 9).

Figure 9: Final structure on three supports

4. Conclusion

This research demonstrates a powerful synergy between high-tech design and low-tech manufacturing within the realm of stone architecture. By blending complex geometry-based design capabilities informed by the Triply Orthogonal Systems of Surfaces (TOS) with the practicalities of manual stone construction, we have successfully implemented an innovative interlocking stone vault prototype. Key to our approach was the reciprocal influence between design and construction phases: knowledgeable practitioners in construction, like Paul Vergonjeanne, enriched the design process with their suggestions, advice, and ideas. Conversely, Paul Nougayrede, Aly Abdelmagid, and Anahita Mirani as designers, who were deeply involved in the actual construction, faced firsthand the fabrication challenges. This involvement significantly enhanced their understanding of the material and structural behaviors, which will inform future design decisions.

The successful implementation of a stone vault prototype in less than four days, by a team of architecture students and stonemasonry trainees, is a testament to the efficacy of this symbiotic design and construction process. This project not only demonstrates the feasibility of combining high-tech design processes with simple manufacturing techniques but also emphasizes the educational value of such hands-on involvement.

Looking ahead, potential directions for further research include refining our design methods by incorporating explicit analytical formulations of the explored surfaces based on the TOS, and exploring more complex morphologies through transformations such as Möbius transformations. This could lead to the determination of an optimal network of blocks that minimizes variations in relative dimensions, enhancing both functionality and aesthetics. Additionally, we see potential in refining the construction techniques by integrating bolted or bonded peripheral joints to optimize the assembly process, potentially improving the structural integrity and sustainability of the constructions.

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References

[1] M. Brocato, "A method to design stone structures based on origami," *Mech. Mater.*, vol. 182, p. 104646, Jul. 2023, doi: 10.1016/j.mechmat.2023.104646.

[2] A. V. Dyskin, Y. Estrin, and E. Pasternak, "Topological interlocking materials," *Springer Ser. Mater. Sci.*, vol. 282, pp. 23–49, 2019, doi: 10.1007/978-3-030-11942-3_2.

[3] Y. Estrin, V. R. Krishnamurthy, and E. Akleman, "Design of architectured materials based on topological and geometrical interlocking," *J. Mater. Res. Technol.*, vol. 15, pp. 1165–1178, Nov. 2021, doi: 10.1016/j.jmrt.2021.08.064.

[4] M. Fantin, "Étude des rapports entre stéréotomie et résistance des voûtes clavées," 2018.

[5] Z. Ma, "Equilibrium Analysis of Topological Interlocking for Structural," *Mass. Inst. Technol. MIT*, no. 2017, 2017.

[6] S. Feldfogel, K. Karapiperis, J. Andrade, and D. S. Kammer, "Scaling, saturation, and upper bounds in the failure of topologically interlocked structures." arXiv, Dec. 22, 2022. Accessed: Oct. 10, 2023. [Online]. Available: http://arxiv.org/abs/2212.11554

[7] T. Siegmund, F. Barthelat, R. Cipra, E. Habtour, and J. Riddick, "Manufacture and Mechanics of Topologically Interlocked Material Assemblies," *Appl. Mech. Rev.*, vol. 68, no. 4, 2016, doi: 10.1115/1.4033967.

[8] A. T. Kurucu and Z. Y. İlerisoy, "Structural Performance of Topologically Interlocked Flat Vaults According to Joint Details," *Period. Polytech. Archit.*, vol. 54, no. 1, pp. 1–11, 2023, doi: 10.3311/PPAR.19509.

[9] O. Tessmann and A. Rossi, "Geometry as interface: Parametric and combinatorial topological interlocking assemblies," *J. Appl. Mech. Trans. ASME*, vol. 86, no. 11, 2019, doi: 10.1115/1.4044606/960599.

[10] V. Loing, O. Baverel, J.-F. Caron, and R. Mesnil, "Free-form structures from topologically interlocking masonries," *Autom. Constr.*, vol. 113, p. 103117, May 2020, doi: 10.1016/j.autcon.2020.103117.

[11] O. Tessmann, "Interlocking Manifold Kinematically Constrained Multi-material Systems," in *Advances in Architectural Geometry 2012*, L. Hesselgren, S. Sharma, J. Wallner, N. Baldassini, P. Bompas, and J. Raynaud, Eds., Vienna: Springer Vienna, 2013, pp. 269–278. doi: 10.1007/978-3-7091-1251-9_22.

[12] M. Brocato and L. Mondardini, "Parametric analysis of structures from flat vaults to reciprocal grids," *Int. J. Solids Struct.*, vol. 54, pp. 50–65, 2015, doi: 10.1016/J.IJSOLSTR.2014.11.007.

[13] M. Brocato, W. Deleporte, L. Mondardini, and J. E. Tanguy, "A proposal for a new type of prefabricated stone wall," *Int. J. Space Struct.*, vol. 29, no. 2, pp. 97–112, 2014, doi: 10.1260/0266-3511.29.2.97.

[14] M. Brocato and L. Mondardini, "A new type of stone dome based on Abeille's bond," *Int. J. Solids Struct.*, vol. 49, no. 13, pp. 1786–1801, Jun. 2012, doi: 10.1016/j.ijsolstr.2012.03.036.

[15] A. Abdelmagid, Z. Tošić, A. Mirani, A. Hussein, and A. Elshafei, "Design model for block-based structures from triply orthogonal systems of surfaces," *Adv. Archit. Geom. 2023*, pp. 165–176, 2023, doi: 10.1515/9783111162683-013.