

# Design to fabrication integration and material craftsmanship

*A performance driven stone architecture design system based on material, structural and fabrication constraints and criteria*

*Sina Mostafavi<sup>1</sup>, Matthew Tanti<sup>2</sup>*

*<sup>1</sup>PhD Candidate, TU Delft <sup>2</sup>MSc in Architecture, TU Delft*

*<sup>1</sup>www.hyperbody.nl <sup>2</sup>www.rapidstudio.nl*

*<sup>1</sup>s.mostafavi@tudelft.nl <sup>2</sup>m.tanti@student.tudelft.nl*

*This paper presents a computational design methodology through describing of a case study on stone building system. In addition to establishing a performance driven form-finding methodology, the objective is to redefine local craftsmanship methods as industrial fabrication techniques in order to introduce the constructability of the design solutions as one of the main performance criteria. Therefore, the focus of the methodology is to facilitate architectural design processes through developing of customized computational design tools and workflows for data integration and concurrent performance evaluation. The research starts with the hypothesis that the technological advancements in digital design and fabrication can lead to re-exploration and improvement of traditional building techniques with local materials. The paper explains different stages of the methodology and the way the chained design to fabrication processes would lead to constructible, structurally possible and optimal design solutions of small scale and simple symmetric design solutions to complex topologies at the scale of larger complex buildings.*

**Keywords:** *digital materiality , design information exchange, compression-only stone structure, Computer Aided Craftsmanship , robotic fabrication*

## INTRODUCTION

The case study and the described design process in this paper will challenge the performative limitations of working with stone as a purely mass produced material. Through the development of a methodology for data integration and information exchange between different computational subroutines, the

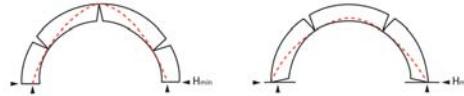
goals is to extend the performance of stone architecture through mass customization of the individual stone elements. With these objectives in mind, the research investigates into the vanishing discipline and building technique of stereotomy, a building system which has been in decline since the industrial revolution and its knowledge is in danger of getting

lost due to its extensive demand for high level craftsmanship and geometrical knowledge. Through the use of digital design and fabrication these requirements could be met and also exceeded, enabling new opportunities for re-interpretation and improvements in the performance of this material system.

Considering the aforementioned goals and challenges at fundamental and theoretical level this research tries to answer first this question of what kind of architecture could emerge if we shift from the modernist paradigm of mass production and importation of foreign materials; and focus on local materials, high-level craftsmanship and mass customization through robotic fabrication? Secondly, it questions how can computer aided craftsmanship help us re-explore the vernacular in a contemporary way and extend the performance of a local material system? Furthermore, more specifically at technical level the focus of the research is on developing reusable and generic computational design to fabrication workflows for design and construction of buildings using stone building systems.

The study does not see digital fabrication as a unidirectional process, but a bidirectional communicative process where the material properties are also digitized and simulated. This allows for both material and fabrication characteristics to be applied in an integrated manner for the same architectural goal. At theoretical level this idea can be traced in the works of contemporary philosophers such as DeLanda that brought the idea of material morphogenesis in which by 'teasing' a particular material a form emerges out from its properties rather than being imposed on it (DeLanda 1998). Therefore the first step adopted in heading towards an integrated design approach in stone masonry structures was the study of the material itself. Stone's physical properties is dependent to the region and formation process. From the three main stone types, (igneous, sedimentary, metamorphic) the article focuses on sedimentary stone. The material's inability to resist tension stresses was the leading factor why a compression only structural system was adopted throughout the whole process.

Such a system eliminates flexural stress on the material by taking full advantage of form. This geometric requirement introduces us to the concept of the 'thrust line', a theory well documented by Jacques Heyman (Heyman, 1995), which is illustrated in the Figure 1.



The study is based on a design case where the reader is guided through the four basic steps applied within this integrated design system. In this chained design to fabrication system the several common inputs are defined and the outputs of each stages will be the input set of the other stages. The challenges and the developed methods for design information exchange and translation of the output data sets will be described. Moreover, through the processes the article gives a brief review on the computational tools based on graphic statics and spring-based particle systems to introduce the state of the art in this field of research. Furthermore, a brief review on the hardware and software used to robotically cut the stone is also given. This review gives a solid reasoning for the choice of technologies and applications chosen. During the elaboration of the process, the study is concerned about the following questions:

- How a dynamic design information exchange can facilitate the design processes to have more flexibility both in term of generating semi optimal solutions and selecting the desirable alternatives by the designer?
- How to interconnect a multitude of different factors for different performance criteria in order to achieve an integrated design to fabrication procedure?
- How to integrate various processes of performance mapping and simulation? In this case,

Figure 1  
Thrust line in dotted red. Hinges develop when thrust line is not in held the section of the material

how to integrate structural analysis in the assembly process in order to introduce local differentiation in thickness?

The final section of the paper, shows how this methodology can be used in a more complex architectural project where the design intent, context and program have an important impact on the final topology and morphology.

## **THE DESIGN CASE AND THE METHODOLOGY**

The study deals with the challenges involved in working with topologies where two (or more) vaults interconnect; a problem which has not been tackled deeply yet. The reason for considering this type of topology is to give more flexibility to the design system for form finding of more complex geometries at larger building scales. These kind of topologies pose a challenge to already well established methods of simulating equilibrium in compression only structures with existing tools that proves to be accurate and a robust for single shells, but their fundamental computational logic and process does not support interconnected shells. Therefore the chosen topology required an alternative method of form finding. In following sections the descriptions of the four interconnected stages of the process clarify how this challenge is tackled and how the structural and fabrication constraints and criteria are considered and embedded in the design system.

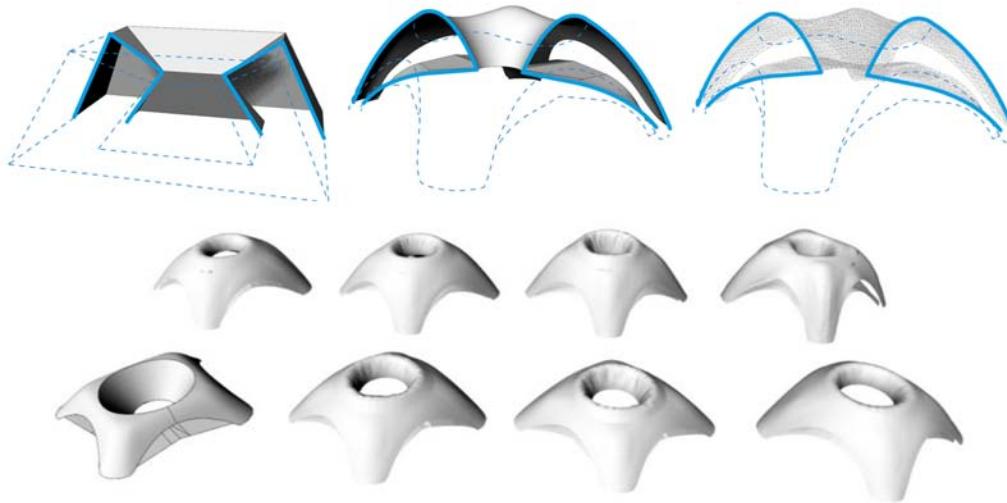
### **STAGE 1: FROM MATERIAL PROPERTIES TO GEOMETRIC REQUIREMENT**

In this stage, having a clear idea of the topology is the starting point. The prototypical topology used for this design case is kept simple for clarity and ease of understanding the method developed and applied. In an architectural design context, this topology is solely influenced by the design concept for every specific project. The topology in question can be seen as two vaults at top each other as seen in Figure 2. The inner supports of the top vault are located on the apex of the bottom vault, meaning that

forces from both vaults have to interact and behave as a whole for the structure to be statically equilibrated. To run these hanging chain simulations, a spring-based particle system was used in connection to the physics engine Kangaroo in Rhino Grasshopper. To do this, it is important to have a sealed digital model where no naked edges exist between the different parts.

In the early stages, topological experimentations were done by manual modeling, converting the NURBS (Non-uniform rational B-spline) surfaces into a mesh, and further transforming the mesh edges into springs for relaxation. For further refinement of the relaxed result, a series of iterations were needed. This led to create a parametric chain geometry which was able to adapt quickly depending on the architectural needs (Figure 2). Apart from the alteration of the chain geometry itself; the anchor points, the springs' stiffness and the loads imposed also give rise to other variations. In this case, rather than imposing a specific geometry on a material, the geometry of the chain is given by the designer and then, altered accordingly by the dynamic relaxation process to satisfy the geometric requirements for the structure to work in compression only. In this way the system became an interactive tool where a direct communication between top down architectural decisions and bottom up structural geometric requirements come together to find an informed balance between the two; relating back to the philosophical concepts of material morphogenesis. In this particular case, the only hard criteria involved in choosing a semi-optimal option was based on structural validation through FEA software and making sure the compression stresses does not reach the compression strength of the material (Figure 3). Other softer criteria involve the height, quality of the space enclosed and overall visual proportions of the structure. Since the relaxation process gives a mesh geometry as an output, the resultant geometry can be directly used as input for a different number of performance analysis criteria. For future studies solar radiation and thermal mass calculations could also affect the over-

Figure 2  
 Top left:  
 topologic study,  
 Top middle:  
 parametric chain  
 topology,  
 Top right:  
 mesh to springs,  
 Bottom:  
 iterations



all form and more specifically in this case differentiation in the thickness and the challenge is to see how such conflicting performance criteria could be considered simultaneously.

### **STAGE 2: FROM GEOMETRIC REQUIREMENTS TO THICKENED SHELL**

In this stage, the process focuses on introducing differentiation in the thickness of the shells to control material distribution and structural performance of the design. Rather than giving the shell one global thickness the process explores the idea of using structural analyses to inform the design system to differentiate the local thicknesses. Again in this stage differentiation in the thickness of the shell can be influenced by other simultaneous simulations like solar radiation and thermal mass calculation.

The concept of differential local thickness in this study shifts towards the assembling process, and how this can be beneficial. The main principle of a compression only structures is that the thrust network needs to be between the inner (intrados) and

outer face (extrados) of the vault. There might be the case when the section of material in the shell is not thick enough to keep the thrust network within it; this scenario creates tension forces on the shell which could lead to hinges and also collapse. A thicker shell is able to contain a bigger number of catenaries for different load cases, therefore more it's stable (Heyman 1995). When designing compression only structures, it is important to check for stability also while it is being constructed. In this design exercise, the thrust network shown in the Figure 3 only apply when the structure is fully constructed. This means that the structure would be unstable until the top shell is assembled. Figure 4 (Left) shows the thrust network of the bottom shell supporting itself (in red) imposed on the thrust network of the structure as a whole. (blue). Where the two thrust networks deviate from each other, it reveals the need for more thickness for the shell to be stable throughout the whole construction process as seen in Figure 4 (Right).

Figure 3  
Left:  
Chosen dynamic  
relaxation result.  
Right:  
Structural  
validation using  
FEA software.

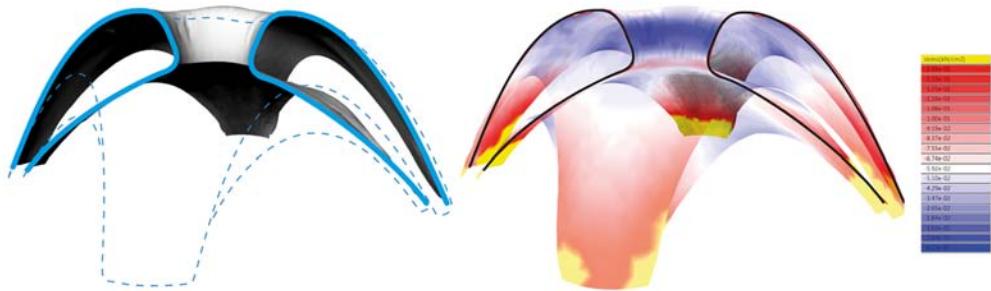


Figure 4  
Studies on  
thickness variation



For the shell to be discretized into individual blocks at a later stage, the geometry needs to be translated back into a NURBS geometry. This gives the flexibility to adjust accordingly and not being bounded by the irregular mesh edges and vertices. The thickness has been created by generating two faces (intrados and extrados) on each side of the thrust network. For optimal structural performance, it is important that the thrust network is in the center between the two new surfaces. The same logic for the generation of the chain NURBS geometry in stage one was used to create the intrados and the extrados. When compared to the high problematic issues involved in converting a mesh geometry to a NURBS curve, this step is rather simple and if care is taken in inputting the right parameters, a high level of precision can be achieved. Due to the fluidity of the digital model, the designer is given full flexibility to adjust thickness where he/she deems fit. In this case the minimum thickness is of (20cm) and gradually get thicker (55cm) towards the oculus or top skylight opening where the two shells meet.

### STAGE 3: FROM THICKENED SHELL TO PERFORMATIVE VOUSOIRS

After determining the local thicknesses of the shell, the structure needs to be subdivided into the individual stone voussoirs or blocks. This stage calls for the full integration of structural constraints, material considerations, aesthetics and craftsmanship. One of the main parameters in stone architecture is the direction and flow of the voussoirs in relation to the thrust network (Block & Rippmann 2011). It is imperative that the shared faces between the stone voussoirs are as perpendicular to the thrust network as possible, with an acceptable deviance of less than 30 degrees. Further deviance would result in slippage of the stone elements and instability of the structure (Huerta 2001). When dealing with sedimentary stone, the orientation of the bedding lines should also be perpendicular to the main principle stress (Cachia 1985). Furthermore it is of utmost importance for the ashlars to have a staggered bond, this creates friction forces along the sides which increases resistance against slipping. Different types of tessellations can be explored as long as the top and bottom faces touch more than one stone voussoir (Block & Riippmann 2011). To achieve such complex discretization of the surface, a relatively simple method was applied. Rather than focusing on intensive computation; topology was used to the design's advantage. The NURBS surfaces created in the previous stage, needed to go through another redrawing se-

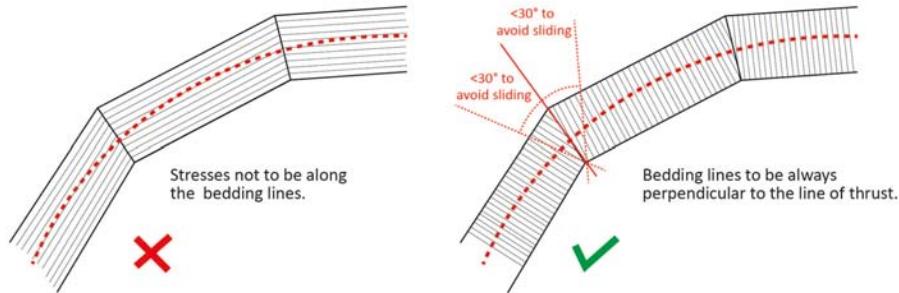


Figure 5  
Thrust network  
perpendicular to  
shared voussoir  
faces and natural  
stone bedding  
lines.

quence before tessellation. In this phase, the geometry is translated from a trimmed surface (Figure 6, top-left) into an untrimmed surface by creating a network surface. By using the surface boundaries as the main curves (red curves in figure 6 top-middle) for the network surface, it guarantees that the flow of the surface iso-curves approximate the direction of the thrust network. The new surface was later split along the lateral direction (green curves in figure 6 top-middle), thus creating continuous longitudinal strips along the surface (along the red curves). These longitudinal strips were further split in a way that the seams between the voussoirs are always perpendicular to the longitudinal direction. By allocating a different number of divisions per strip, and moving the seams of the edges, it was made sure that a staggering bond would always be generated. A safety feature was included in the logic so as to mark any seams which deviate more than a 20 degree angle from the principle stress flows (Figure 6, bottom-left).

For the voussoirs to be robotically fabricable with line-based end effector or head, all the surfaces in the stone voussoirs had to be of a ruled nature. The individual stone elements had to be further articulated to achieve this feasibility. This was done by choosing one specific direction along which the curvature would need to be discretized into straight lines. In this example the curvature in the voussoir was left along the continuous longitudinal direction of the surface. This creates a continuous aesthetic of con-

centric strips along the entire structure. (Figure 6, top-right & bottom-middle) A feature which became useful in the process is the ability to parametrically control the number and differentiate the thickness of the longitudinal strips, this enabled the strips to be thinner and more condensed where the curvature of the vault was higher. This tweaking allowed for the surface to be discretized where really needed thus adhering to the original curvature as much as possible in the lateral direction (along green curves in figure 6 top-middle) The top and bottom longitudinal curves were taken as guiding curves whereas the lateral direction followed the straight geometry of the straight line of the robot end effector (Figure 6, bottom-middle). By keeping these geometrical constraints in mind, further articulation of the voussoirs can be done which would result in a higher degree on performance embedded in the stone element. Figure 6 (bottom-right) shows how the stone block could be further crafted in a way to create thermal breaks and water tightness through removal of the material in the middle layer.

#### STAGE 4: FROM VOUSOIRS TO FABRICATION INFORMATION

The final stage focuses on the fabrication of the actual blocks from the extracted stone megalith. To reduce as much waste as possible, the stone ashlars were grouped together depending on their thick-

Figure 6  
Re-generating  
NURBS untrimmed  
topology and  
tessellation  
procedure.

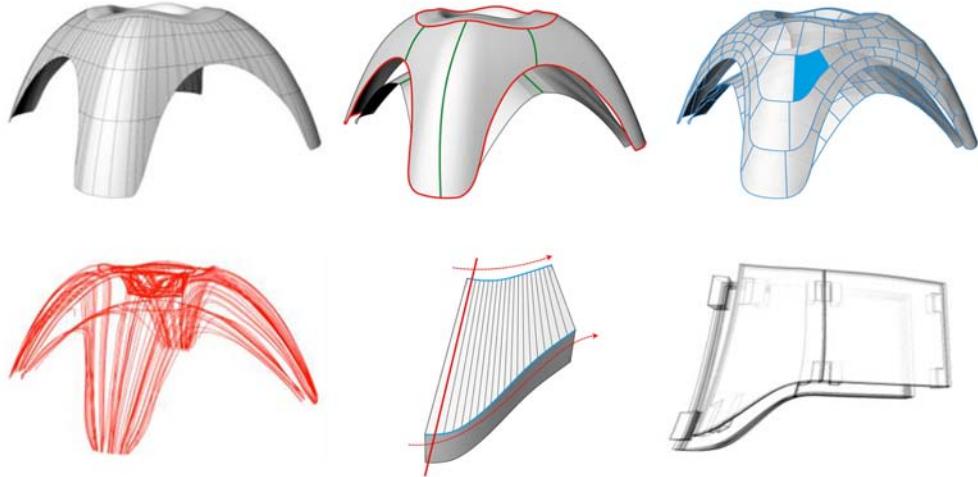
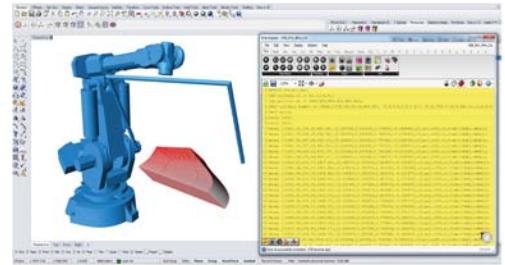


Figure 7  
Rapid Code  
generation through  
Grasshopper  
custom  
components

ness. The individual stone component is nested in a larger stone slab which had been split from the megalith. Apart from minimizing waste as much as possible, the nesting algorithm also aligns the stone ashlars according to the bedding lines in relation to the principle stress flows.

When all the geometry in a particular slab is nested, it is used as input information for the robotic arm simulation. This makes sure that the geometric information in all the stone blocks is feasible before moving from the digital realm to the physical. In this case study the simulation has been done with open source 'Mussel' software, which allows for the transliteration of geometry into ABB industrial robotic arm movements via RAPID code. This simulation sheds light on any overlooked fabrication issues which might cause a break in the production process. The most common breaks usually arise from the limits of the robotic arm's reach and joint rotation. Furthermore, issues such as collisions of the tool with other objects (including the robotic arm itself) may also arise. After the simulation, a dry run is also ad-

vised before going for the actual cut. The speed of the robotic arm and rotation speed of the abrasive wire have to be tested and calibrated depending on the type of stone and finishing required.



## ARCHITECTURAL APPLICATION AND DISCUSSION

The following images (Figures 8,9,10 &11) shows the implementation of such a methodology into a complex architectural project. In this case, the project is situated in the Maltese islands, a place where glo-

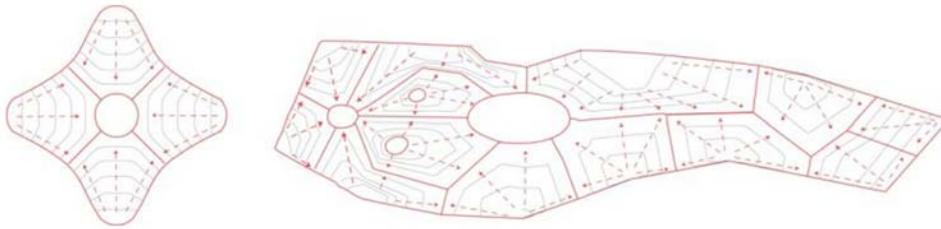


Figure 8  
 left: Design case  
 topology. Right:  
 Topology of  
 implementation  
 project

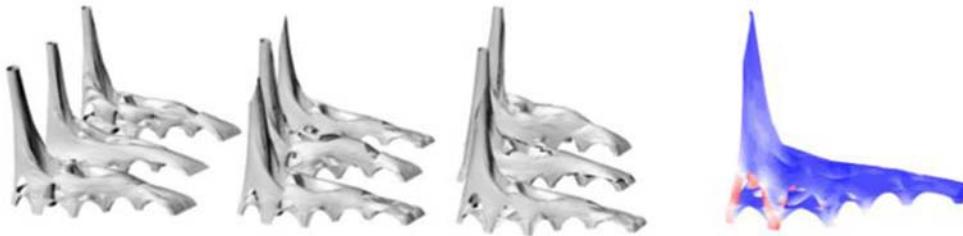


Figure 9  
 Left: Iterations of  
 Dynamic relaxation  
 procedure. Right:  
 Analysis and  
 validation of the  
 result.

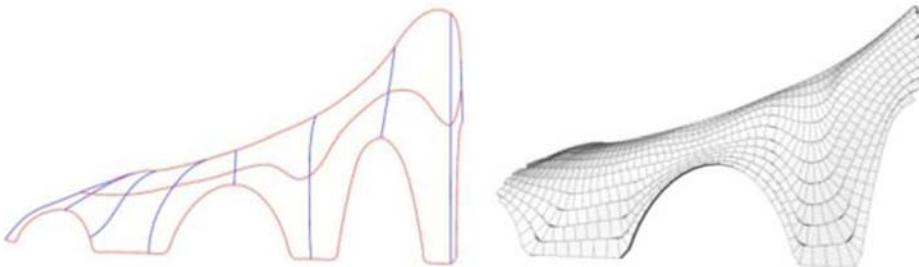


Figure 10  
 Left: Converting  
 mesh geometry  
 into untrimmed  
 NURBS  
 surface. Right:  
 Voussoir  
 tessellation.

Figure 11  
figure 5.7-  
Rendering of final  
morphology in the  
surrounding  
environment.



Figure 12  
Physical printed  
prototype of the  
design case



bigerina limestone is the only resource material available for construction on the island. This system is suited for such a context as this renewed building system could lead to a new type of regionalist architecture where the cultural landscape built in stone throughout its history can keep on flourishing in a new interpretation.

The main distinctive difference between the design case and this project, is the topology. The images below show how the same logic can be applied for a more complex topology. The issue was solved by first defining a central point for every support. These points were used as centre points, where

the voronoi principle was used to divide the shell into manageable part. The applied method also made sure that the shell was split perpendicularly and mid way from the supports. This logic was further tweaked in order to support additional architectural requirements like building program and circulation. Figure 8 (left) shows the logic applied in the paper's design case and figure 8 (right) shows how the same logic was applied to define the topology of the project mentioned.

The techniques of using stone in a freeform masonry architecture brings a lot more challenges and opportunities which can be investigated in future re-

searches and case studies. The authors are interested and encourage further research in how solar radiation and thermal mass calculations could also affect the local thickness of the stone elements or the air gaps between two layers of stone. As future research, we are interested in delving further into the design opportunities found in the heterogeneity of stone and explore how informed material extraction/cutting (through CT Scanning) and design could both influence each other by allowing a bidirectional relationship. Although the research did consider the process of assembly, there is a lot more to be explored and detailed which would result in more efficiency on site through the reduction of falsework needed to prop the structure before achieving structural integrity. One other objective is also to find ways how the developed system could be adapted for other fabrication techniques such as the 3D printing of an inert natural material. The following Images illustrates some of the initial physical prototyping with Stereo lithography type of printing with artificial or plastic based material (Figure 12). The hypothesis for the next step can be further formulated based on this presumption that like the way the orientation of bedding lines in sedimentary type of stones is important in structural performance of the stone blocks, it could be important to explore how it is possible to control the direction of the layers of depositing material in printing for better performance.

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