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An exploration of 3d printing design space inspired by masonry

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Abstract

This paper describes an approach of a process-aware exploration of the design space of building components constructed by extrusion of cementitious material (or concrete 3d printing). In an attempt to broaden the geometries that are being printed today, and to build cantilevers, vaults and domes without using temporary support, we look back at construction techniques used in masonry structures, and analyse the stability of the fabrication process at the scale of the brick, the layer and the final structure. Those strategies are applied to 3d printing with regards to the material properties and the technological aspects of the process. Three examples are actually printed to validate the approach, namely a Nubian vault, a dome and an arch, all without temporary support. Finally a framework for generation of printable geometries and corresponding toolpaths is proposed.

Keywords: 3d printing, cementitious material, funicular shell, masonry, digital fabrication, robotics, form finding

1 Introduction

1.1 Context

Additive fabrication of cementitious material - or mortar 3d printing - has known a rapid expansion in the last decade which has led to multiple innovations in term of material rheology, printing technology (robotics and extrusion head) and their applications. Research has focused on finding the best mortar for printing, on the formation of "cold joints" at the interface between layers or on the potential reinforcement of the printed structures. A field that is yet to explore is the design space of printable geometries.

3d printed geometries are limited by the resistance of the fresh material and the printing process. Non standard geometries have been achieved by use of external supports [5]. However, it is not satisfying as a sustainable solution due to costs and environmental impact of such temporary structures. The challenge is hence to solve the problem of printing free of temporary support and yet without loosing architectural freedom or structural efficiency.

This paper proposes a geometry exploration of printable structure that does not require external support. In a first part we look at 3d printing processes that have been developed so far based on two asymptotic strategies in terms of material and technology. Then in a second part, we present three examples of ancient masonry brickworks and their implementation using 3d printing process. Finally we propose a framework for generation of geometries and corresponding toolpaths.

1.2 Previous works

Based on what has been done so far by the different actors in the field of 3d printing - academics or industrials actors - the strategies in place can be bounded by two asymptotic strategies in terms of material properties described by Roussel in [7], robotic complexity and control of the process.

- a **pure extrusion process** which is the most common strategy in use up to this day. It consists in printing with a 3-axis robot (namely a printing head mounted on a gantry bridge) moving in Cartesian coordinates, extruding a material that does not go through a phase change and which has an initial yield stress relatively high (500 Pa to 1kPa). The shape of the layer is given entirely by the shape of the nozzle. The extrusion occurs in successive horizontal planes (some talks of 2.5D printing) and the only way for this technology to create global cantilever is by creating corbels with the layers (local cantilevers).

- a **sheared material deposition** is the opposite strategy using a 6-axis robot to print layers that are not inevitably horizontal. This strategy is introduced in [4]. The mortar used goes through a phase change in the extrusion head by addition of additives giving to the material a low initial yield stress (100 Pa) but a high structuration rate. The layer is shaped by squeezing it between the nozzle and the previous layer. Different layer's heights can be obtained just by changing the printing parameters.

As Pegna mentioned in [6], 3d printing can be seen as a new approach to masonry. 3d printing and masonry are additive manufacturing processes sharing the disadvantage of using a material with a poor tensile strength. Historically, masonry builders have developed strategies to overcome this issue and build cantilevered structures without the use of temporary supports. From these strategies, many of which are detailed in [2] by Auguste Choisy, we can cite the creation of corbels, the inclination of layers of a dome, the construction of barrel vault by successive inclined arches or the development of squinches by the Persians.

1.3 Method statement

Due to the poor mechanical properties of the fresh mortar, 3d printing main difficulty lies in the stability of the structure during the fabrication. By analogy to masonry, this issue can be tackled at different scales. The scale of the section when the material is extruded, the scale of the layer and the scale of the overall structure in its final configuration. In this paper, we explore similarities between masonry and 3d printing through three examples. Each representing a topology and a construction strategy developed by masonry builders. We analyse the printing parameters at play for the realisation of such structures, in terms of material properties and fabrication technology. The aim is to push the boundaries of the design space of printable geometries and propose a framework for the design of such structures and the generation of corresponding toolpaths.

2 Masonry and 3d printing

2.1 Planar cantilever

2.1.1 The geometry

The first example is an opening in a wall, so a cantilever in two dimensions. The crossing takes the shape of a pointed arch. The wall is made of a double layer for two purposes. First, this is a way to have a closed toolpath and avoid having to stop and start the printing set up. Secondly, it allows for the overall thickness of the wall to evolve with the height. It is wider at the base than at the top, providing more stability to the wall. Fig.1 illustrates the geometry of this two dimensional crossing.

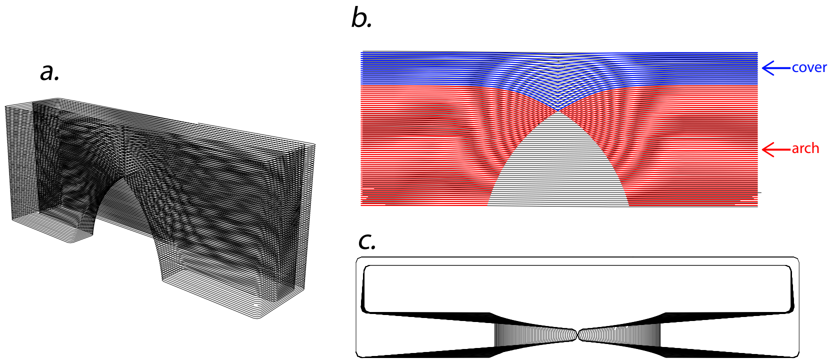

Figure 1: Toolpath of the 2D crossing. a.*3D view*, b. *front view* with distinction between upper and lower parts, c. *top view*

The main difficulty in this example is to ensure the local stability of a layer around the opening, by avoiding the material to flow after the extrusion. The strategy chosen to tackle this problem is to incline the layers in order to avoid any local cantilever in the layer which would create bending.
By doing so, the contact surface is maximised between two consecutive layers, and the material only sees pure shear stress.
This is achieved by slicing the geometry not horizontally as it is usually the case, but by offsetting the layers on the object surface with a constant distance, until the two half-arches connect. This can be done using Adiels *et al.* slicing algorithm described in [1] and initially intended for masonry structures. The result is a set of layers that bend downwards near the opening (see Fig.1.b). In the upper part (the *cover*), the distance between layers increases locally to compensate gradually for the non-planarity of the layers until reaching a horizontal level.

2.1.2 The printing process

In practice, the printing head connected to the robot rotates so that the extrusion nozzle remains tangent to the surface of the object at all times. This makes full use of the 6-axis robot and its capacity to reach any target in space with different orientations. The strategy described above ensure the stability of the material locally, just after the extrusion.
The overall structural system of each half of the wall that ensure global stability until the arch is complete, is inspired by a construction technique used to build Gothic vault without formwork (see Fig.2.*left*). The cantilever structure itself remains in compression thanks to the

stone-weighted rope device, working in tension. In our case, the tensile stresses are located in the walls. For such a structure, reinforced concrete could help achieve much higher cantilevers.

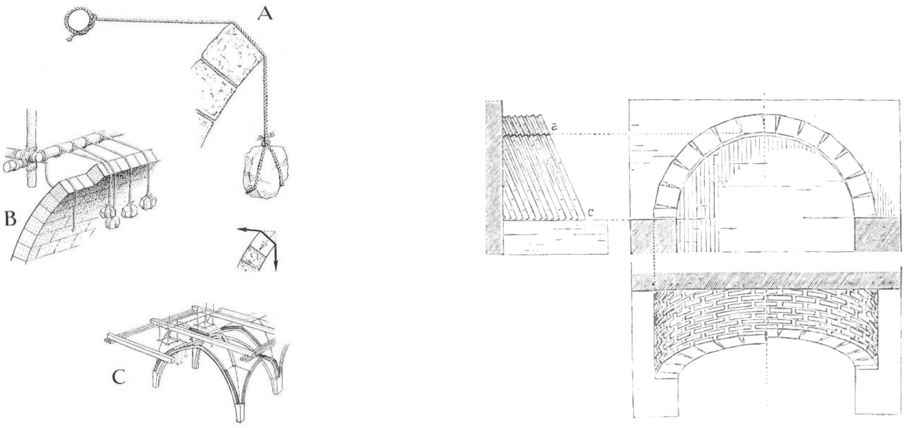

Figure 2: *left:* The stone-weighted rope device for erecting Gothic vaults (John Fitchen, *The Construction of Gothic Cathedrals, 1961, fig. 69, p.182*), *right:* Nubian vault construction by Auguste Choisy from "L'Art de btir chez les Byzantins"

In practice the printing process can be divided in two part, one for the bottom and another for the upper part of the object.

- in the lower part, all parameters - printing speed and extrusion flow rate - are kept constant.
- in the upper part, the flow rate q_c is kept constant. In order to compensate for the thickness increase in the layer and keep the same width d, the speed c_r is decreased locally with respect to mass conservation relation 1.

$$Q_c = c_r \cdot h \cdot d \tag{1}$$

with Q_c the flow of concrete, c_r the speed of the robot, h and d the height and width of the layer.

Figure 3: Wall opening

2.1.3 Observations and limitations

In this example, we managed to print a two dimensional arch (see Fig.3) with a global inclination of 37° and a maximum local inclination up to 60° in the upper part of the arch. This demonstrates the local stability of a layer even with high inclination can be achieved given that the material's initial yield stress is sufficient. Consequently, a global cantilever can be obtained by 3d printed.

2.2 Translated vault

The second example is a barrel vault, built with a technique developed by the Nubians in Egypt, examples of which are still standing after over 3300 years. This technique allows to built barrel vault without any temporary support. The construction can then be assimilated to a horizontal extrusion of an inclined arch, where each layer is supported by the previous ones (see Fig.2.*right*).

2.2.1 Construction sequence

Throughout construction of a Nubian vault, each layer experiences three phases in terms of stresses. By considering one layer in particular, the three phases are as follows:

- The first phase corresponds to the extrusion of the material. At this stage, it has to withstand its own self-weight to avoid local collapse of the layer. Since the layer is inclined, the stress in the material is higher than when extruded horizontally. The material's initial yield stress must be adapted to the layer inclination angle θ.
- once the layer is fully in place, it starts behaving as an arch in compression. In the same time, it has to withstand the loads brought by successive new layers. In 3d printing, that means, the structuration rate of the material A_{thix} has to be sufficient so that the stress accumulated by the addition of layers stays below the yield stress τ_c at all times. The higher the angle with the vertical θ is, the higher is the influence of the new layers.
- the third phase appear when the addition of new layers has no influence anymore on the stress state of our considered layer. Since the structure evolves horizontally, the layers are not continuously loaded as in vertical extrusion. This characteristic of Nubian vault fabrication make them not limited in length.

To summarise, if $\theta = 0$ (layers are vertical), the initial stress in the material is maximum but the layer reaches its final state quickly. With a high inclination angle θ, the initial stress is lower but the permanent regime is reached later.

2.2.2 Toolpath generation

The geometry of the vault is generated using form-finding method leading to a funicular shape under self-weight. The vault once finished, is fully in compression. This is permitted by the absolute precision of a robot in space. Indeed, for a masonry vault built manually, the shape has to be approximated by arcs of circle, so that a mason can follow the geometry using simple tools (wire, level, etc.). This shows that architectural freedom brought by digital fabrication can support a design process where shape follows forces.

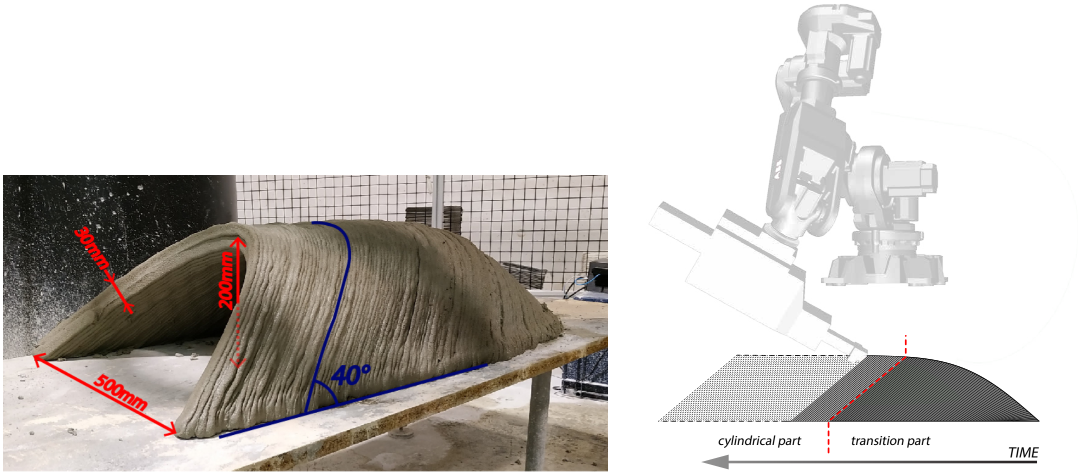

Figure 4: *left:* 3d printed Nubian vault and its dimensions - *height*, *width*, and *thickness*, *right:* slicing of the vault

In masonry, the Nubian vault usually takes support on a vertical gable wall (see Fig.2.*right*). This lead to discontinuous first layers and it has to be avoided for 3d printing process due technical difficulty to stop and restart the set-up. The 3d printing vault then has to start from a fully horizontal layer before shifting to inclined arches. Fig.4 shows the dimensions of the printed vault.

In this example, the layers are all planar. They come from the intersection of the vault surface with a set of planes. In the transition part, the planes inclination gradually increase from horizontal to 40°. This inclination is then kept constant all the way through the cylindrical part (see Fig.4.*right*).

The frames describing the orientation of the robot are generated from those layer curves. For each point on the curve, we define the vector tangent to the curve and the vector normal to the vault surface. The extrusion nozzle orientation is given by the cross product of those two vectors (illustrated in Fig.5). This way, the contact surface between two layers is maximised and always the same. In practice, by adding the robot accessibility constraints, the maximum inclination of the frame with the horizontal is set to 60° (this angle is reached at the apex of the vault).

As a result, the path of the robot is planar, but its orientation gives torsion to the layers. The final step in the generation of the toolpath is the setting of the printing parameters. For this vault, the speed of the robot in the cylindrical part is set at 200mm/s, keeping a constant inter-layer time of 10s.

2.2.3 Results

This example validate the possibility to 3d print barrel vaults without temporary support in a similar way it is done in masonry. It shows that the material can be printed with an inclination up to 60° without collapsing, pointing out in the same time the pertinence of a 6-axis robot to broaden the range of printable geometries.

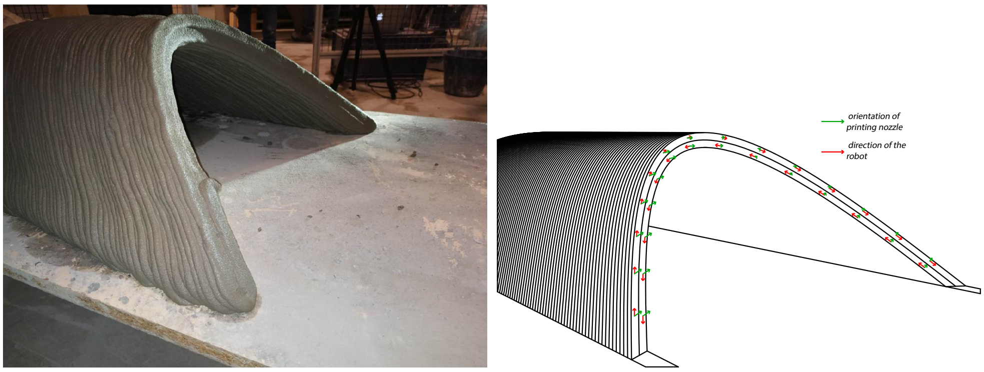

Figure 5: Printing path and local orientation of the extrusion nozzle

2.3 Dome

The last example is a dome with a square base. Circular squinches are generating at each corner and spandrels link them together to reach a horizontal circular perimeter (see Fig.6). From there up, the geometry consists in a simple hemispherical dome, described by Cowan as a *true dome* in [3]. The slope of the squinches in the corners have an inclination of 45°.

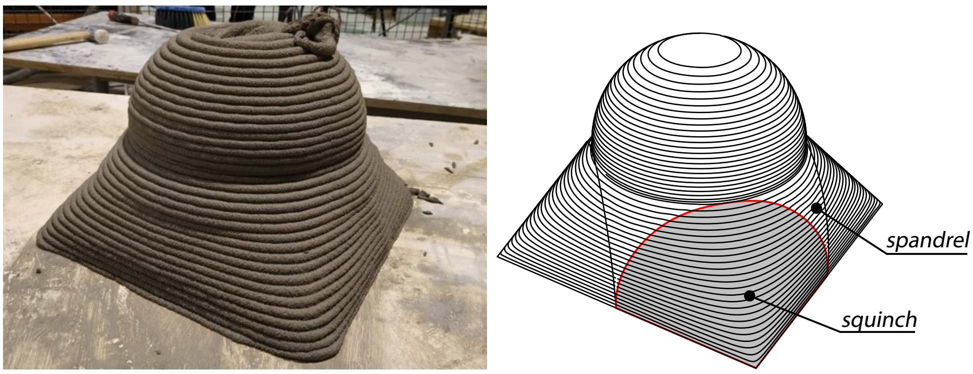

Figure 6: Dome on squinches

The goal of this example is to show the potential and imitations of printing with a 3-axis robot, moving in Cartesian coordinates and hence unable to modify the orientation of the nozzle. The layers are all horizontal, and the height between them is constant.
In addition to that, all the parameters remain unchanged during the printing. Consequently, the cantilever is made by corbelling layers on top of each other and creating local cantilevers. In this configuration, the material requires a high enough initial yield stress. Once a layer is complete, the stability is ensured structurally by the apparition of compressive rings.
The slicing strategy used for the generation of the geometry and the toolpath is simple and fast compare to the ones described in previous parts. However, it comes with limitations:

- the local cantilevers of the layers induce bending in the material. Since this cantilever increases with the inclination of the surface of the dome (see Fig.7.*left*), the stress in the material gets higher as the print goes. This leads to a local collapse of the layers closed to the top of the dome.

- in addition to the increasing stress in the material, the geometry of the structure makes the layer's length decreases the more it goes up (Fig.7.*right*). Since the robot speed is constant, the inter-layer time decreases proportionnally to the length. Thus the last layers have less time to build thixotropy and increase their yield stress accentuating the risk of failure.

To summarise, this strategy advantages lay in the simplicity to generate the toolpath for the robot and the easy movement of the robot reducing the risks of clashes and simplifying the calibration process. On the other hand, the slicing eventually leads to an increase of the stresses in the material, accentuated by an increase of the loading rate.

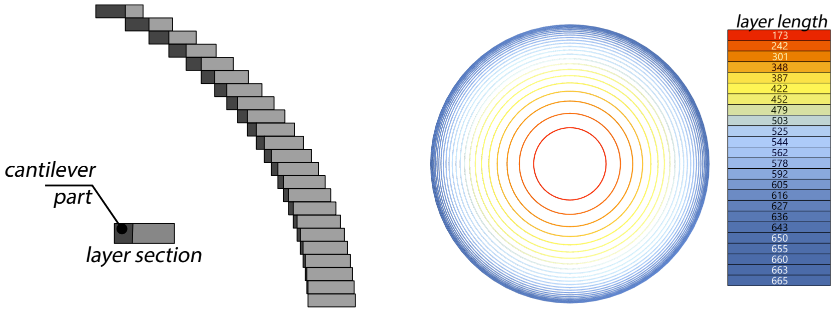

Figure 7: *left:* effect of corbelling on a spherical dome with gradual increase of the cantilever, *right:* decrease of the layer's length (in mm)

3 Results

The examples presented in this paper help to show the similarities between masonry construction techniques and mortar 3d printing process. Using different structural typologies, namely a two dimensional opening, a barrel vault and a dome, we can draw general conclusions in regards to printable geometries and toolpath generation. The challenges being to ensure stability of the printed object during fabrication and mechanical efficiency of the final structure accounting for the material used.

Those examples show that 3d printing process faces challenges of stability at different scale. The local scale of the component, where the material must withstand its on weight as soon as it is extruded. The strategy chosen to perform the global cantilever, is translated at the layer's scale to either a local cantilever inducing bending moment in the material, or an inclined layer, where contact is maximised between layers and the stress is mainly shear. At the scale of the layer, a structural subsystem is set in place - arches for the barrel vault, or compression rings for the dome - that ensure its stability by making the material work mainly in compression. Finally, both for masonry and 3d printing, the targeted final geometry must be as closed as possible to the funicular of the structure under its own weight. The structure is then fully in compression, and the lack of reinforcement can be justified.

The aim of the authors is to generalised this process to free-formed shapes in order to extend furthermore the design space of printable geometries.

4 Conclusion

This paper presents an exploration of printable geometries, aiming at building structures without the use of temporary supports. It shows the possibility to print cantilever structures even with a material with poor tensile strength and in this way, validates the approach of finding inspiration in masonry techniques. The problem of stability of the structure is tackled by dividing it in different scales, the scale of the material just after the extrusion, the scale of the layer and the scale of the final structure.
Eventually, expending the boundaries of printable geometries can address the need for architectural freedom while providing answers to environmental issues such as wastes generated by complex temporary structures and a solution to reduce fabrication costs and delays.

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