Fabricating Stereotomy

Variable moulds for cast voussoirs

Pedro De Azambuja Varela¹, José Pedro Sousa²
¹,²Faculty of Architecture, University of Porto + DFL/CEAU/FAUP
¹,²{pvarela|jsousa}@arq.up.pt

Recent developments in digital design and fabrication tools have led architects and researchers to renew the interest in stereotomy. This interest converges with a growing ecological and economical conscience that matches classic stereotomy raw material needs: compression resistance materials. However, material resources or prefabrication time are still major counterparts for the adoption of this construction system. This paper focuses in exploring techniques that profit from the interdependency between built form and fabrication technique, foraging methodologies that allow for stereotomic block creation with simpler resources. The premise is to explore faster, cheaper, more accessible ways to build stereotomic structures. The technique developed in this research explores alternatives to the traditional cutting of stone by expanding techniques for variable moulds to form solid voussoirs.

Keywords: stereotomy, voussoir, mould, variable production, robotic fabrication

INTRODUCTION
Stereotomy, as a construction technique, is only successful if a relatively accurate control of the voussoir’s (i.e. stereotomy construction block) physical geometry is attained. Traditionally this is dependent on very skilled craftsmen or multiple axis CNC machines. If pre-digital stereotomy mainly resorted to planar, spherical and conical sections, post-digital stereotomy encompasses a wide array of free-form surfaces made possible by the digital tools (Fallacara, 2009). Stereotomic voussoir geometric complexity is directly characterized by the technical possibilities available to produce them.

Carving a voussoir from a block of stone can be considered an act of beauty compared to that of classic sculpture. Just as its classic sibling hand labour method, digitally carving through milling is also a fabrication method very prone to material waste, as much as it is time consuming. Additive fabrication lends itself to minimal material waste; casting into an existing mould is the most direct additive fabrication method. The technique developed in this research expands on moulding techniques to form voussoirs in an attempt to tackle these problems.

Forming is typically dependent on one-off moulds, which generates mass production (lack of variability); on the other hand, mass customization of moulds currently results in heavy expenditure (lack of economic feasibility). Digitally customized mould technology has been applied for concrete moulding. One of these techniques relies in a technically complex apparatus based in a matrix of pin actua-
tors which interpolate a free form surface that acts as mould surface (Pedersen and Lenau, 2010; Schipper and Janssen, 2011; Gramazio and Kohler, 2011); another approach is having a digitally controlled end effector to smooth a clay or sand box until the desired shape is attained so that wax can be poured and consequently concrete can be cast (Heikkilä, Vähä e Seppälä, 2015). Although both these systems are successful in shaping double curvatures, only one continuous surface is controlled; in stereotomy application, one can imagine this surface to represent either the intrados (inner face) and extrados (outer face).

Stereotomic construction efficiency is dependent on the geometric accuracy of the contact face; the intrados or extrados should follow the normals to the thrust surface (Rippmann, 2016), although most of the times are subject to aesthetics. This specificity of stereotomy allows us to shift the focus of design and fabrication from the visible surfaces (intrados and extrados) to the contact edges, taking advantage of the fact that many materials are easily available or produced in slabs, with their largest area opposite faces parallel to each other (Kaczynski, McGee and Pigram 2011; de Azambuja Varela and Merritt 2016; Rippmann 2016). The technique developed in this research draws on a balance between constraints and possibilities, expanding on the swiftness of construction while keeping a high degree of formal freedom.

PREVIOUS WORK

Digital fabrication of voussoirs
The success of the stability of a stereotomic structure lies in the correct structural design, in using appropriate materials and in the geometric accuracy of the contact faces of each block. This geometric information was classically transferred from paper to stone by hand tools operated by masons. The machine automation of this carving process was first attained with milling tools. Other subtractive approaches have been experimented such as circular saw, cutting diamond wire, of water jet cutting. While the milling process is the most free in terms of resulting geometry, it is also the slowest. A circular saw is much faster, but much more restrictive to planes of two dimensional curves. The cutting wire allows for spatial ruled surface cutting but is highly resource intensive; water jet cutting is bound to short (<150mm) ruled surfaces cutting but is quick and practical. All these processes share the subtractive approach as means to the final fabricated block; applied to a freeform vault composed of varying geometry voussoirs, this is synonym to a large quantity of wasted material.

By using an additive fabrication method, the wasting of raw material is reduced to a minimum. Creating three-dimensional free form blocks with 3D printing would be the ideal additive approach, but current technology constraints still set this concept apart from feasible construction approaches. Another additive method is that of casting, such as precast concrete, adobe or plaster elements, where raw material waste is also barely quantifiable. This technique relies in a bilateral relationship between the mould (negative) and the cast element (positive). Fabricating disposable moulds is currently the industry standard for casting variable geometry elements, with few advancements from the seminal Neuer Zollhof project by Frank Gehry. To address this problem, a few research projects have relied in pin type tooling, effectively creating reusable free form double curvature surfaces for casting material. However, this approach does not fully address the stereotomy problem as the edge faces are not considered and usually fall within a box, failing to meet the geometric unique angles that allow for the correct transfer of compression forces.

Flat panel voussoirs
Taking cues from previous works using flat panels as raw material for stereotomic constructions, two prerogatives for a variable moulding system of stereotomic block fabrication are established as hypothesis: planar intrados and ruled edge contact surfaces (see figure 1). Typical casting is made into a box of some sort, and this idea is transported to our prerogatives: the bottom of the box shall be the intra-
dos surface, and the walls should reproduce the contact surfaces geometry. A clear advantage of having a solid mould is that its geometry is quite stable, resulting in a very accurate cast. By using a variable geometry system, instability is an added negative factor and should be minimized to the maximum extent possible. A strategy for avoiding geometric inaccuracies is by using the shortest path method for creating a line; by defining a large set of lines connecting consecutive points of two skew lines we get a unique doubly ruled surface. This geometric principle drives the physical experiment described below.

**EXPERIMENT DESCRIPTION**

**Fabrication apparatus**

For creating the casting container, the voussoir faces to be replicated shall be the intrados and contact surfaces. The intrados is created with a planar material, and the contact surfaces with a stretched material between two skew lines, materialized by straight edge pins (see figure 2). Materialization of this concept should follow some guidelines:

- The stretchable material band should be flexible enough to always contain straight lines connecting the pins; on the other hand, it should avoid bulging in the normal direction;
- The pins should be allowed to exist along any vector with any origin in the base plate; this vector is bounded to less than pi/4 amplitude from the base plate (intrados) normal due to stereotomic constraints;
- The pin should be fixed in position with enough strength as not to give under the stretched material, but easily relocated as to generate a new stretched band geometry.

From an ideal point of view, each pin should be controlled individually to swiftly follow a specific spatial vector, changing position (coordinates) and direction (polar and azimuth angle); a clear possibility for this would be to electronically control each pin, or assign an articulated robot for each pin. As this kind and quantity of equipment is not widely available, an alternative was devised: use one robot to drill a hole for each pin that should tightly fit into the hole so that it won’t move sideways, but may be put into place and taken out without destroying the base plate. This plate should be thick enough to allow for a solid grip and soft enough to drill; 40mm plywood was chosen by fixing two 20mm boards together. During the experiment, it was found that a large number of groups of holes could be made in the same base plate, minimizing the waste of this material.

The rubber band should bridge every two consecutive pins; for simplification purposes it was found that one single band around all the perimeter of the block would need less fixations and hardware, contributing to a cleaner surface. Similarly to the digital description of a closed curve, this band has its start and end points in the same pin. The start of the band is always fixed to the pin, and the end of the band slides under the metal tab and fixed when it is stretched enough.

Besides the board, pins and band, an extra element was added to the apparatus: a ratchet strap. This was a remedy solution to the bulging effect in the band caused by the horizontal forces exerted by the casting material. This bulging would not be so evident in the stretching of the band would be carried out by machines instead of pulling by hand.

**Digital work**

**Bottom up principles.** The fabrication strategy is key to define the design constraints of each of the voussoirs and, consequently, the morphology of the macro structure, be it an arch or vault. As considered above, the morphology of each precast element is topologically defined as a prism: the bottom face is perfectly flat, and the side faces are doubly ruled surfaces; the top face gets close to horizontal due to hydrostatics flat, but the viscosity of the material creates opportunities for different morphologies.

Depending on the material used to create the cast element, different constraints may apply. If the material is mainly compression resistant, such as unreinforced concrete or adobe, the structure should
Figure 1
Voussoir geometric relation to thrust surface

Figure 2
Generation of pin location and rubber band adapted geometry
be mainly compressive, resulting in a stereo-funicular form. If reinforcement is added to the casting material, such as glass or carbon fibers, traction resistance may be incorporated to the structural design.

In this experiment unnecessary extra material considerations such as traction resistance were eliminated. Adding this to a quick setting time, plaster was chosen in favour of concrete or adobe.

The area of contact in contact surfaces contributes to the structural efficiency in stereotomic structures. Using flat voussoirs might introduce skew elements, thus reducing this contact surface. As such, another design constraint is the proximity of adjacent voussoirs’ intrados edges.

**Digital design and fabrication.** This experiment relies on digital design tools in two main moments: design and fabrication. For both of these tasks, Rhino’s Grasshopper graphical algorithm editor was used.

The macro stereo funicular thrust surface is a discrete single sheet mesh modelled with Kangaroo using the forces Anchor, Length (Line) and Load. The proximity of adjacent voussoirs’ intrados edges is tackled by the force CoPlanar, which is configured as to bring vertices of the same intrados face to a common plane. This calculation yields discretized planar cells of the thrust surface, each corresponding to one voussoir (see figure 4). At each vertex the normal to the thrust surface defines the normal edges vector which will eventually be the direction of the skew lines that will define the bounding doubly ruled contact faces. For achieving volume, a bounding box based of the thrust planar cell with equal offset to the intrados and extrados side is used to trim the normal edges vectors. This experiment features a natural rubber band with limited elasticity; this elasticity variation was measured with oblique traction and found to be 70mm: this constraint was taken into account as a limit between lower and upper perimeter. As this first version of the fabrication apparatus features a significant diameter pin, this feature was added to the vault visualization by subtracting a cylinder from each corner of the voussoirs.

Digital fabrication was used to drill the angled holes where pins would fit, and also to fabricated the centering and supports. Each vector’s position and direction was calculated according to the pin’s radius, and the groups of vectors were oriented within the boundary of a 600x600 rectangle. In order to optimize the usage of boards for the base plate, a genetic algorithm was used with minimum distance between holes as fitness and XY moving and rotation around the center of each set of holes as genomes. This allowed for a quick calculation of a layout that encompasses all necessary drills (9 sets of a total of 39 holes) in the same wood board (see figure 7). A helical tooling path was created for the smaller diameter mill to carve all the extents of the larger diameter hole.
**CASTING VOUSSOIRS**

This fabrication system theoretically allows for any castable material to be used, such as concrete, adobe or GFRC. The criteria used was the practicality of the experiment, so plaster was chosen for its quick setting time. The first experiment yielded a too fluid plaster that spilled underneath the elastic band; for dealing with the problem it was decided to use a thicker plaster that would not spill; this was achieved by having two different sets of plaster with the same ratio but with different curing times before casting. No demoulding liquid was used; instead, a thin plastic sheet was used to avoid the adhesion of the plaster to the base plate. The first cast used 1/5 of the total material and cured for 120s before being poured as a thick paste that needed to be spread in the bottom but did not spill through the sub millimetric gaps between the band and the base plate. The second cast used 4/5 of the material and cured 60s before being poured as a very fluid material that would create a horizontal surface on top. The casting would be gently rocked to let air bubbles out and let to set for 20 minutes from the second mixing of plaster with water. At this point, the elastic band could be pushed outwards so it detached naturally from the base plate, resulting in the casting of the voussoirs.

**Figure 4**
The various project generation stages, from thrust surface to cast voussoirs.

**Figure 5**
a) Doubly curved surface containing calculated vertices; b) Planarized surfaces, not connecting; c) Connected planarized surfaces

**Figure 6**
Robot drilling angled holes

**Figure 7**
Drilled base plate used for casting all the voussoirs
plaster, and the band could be release to reveal the cast block. The pins were removed tangentially and the block removed as to allow for the final setting. The whole process took less than 40 minutes, allowing for the same apparatus to be used for another block casting.

**CONCLUSION**

The successful decentering of a vault is always somewhat a proof of accuracy of the fabrication system. Although some bulging appeared in the plaster cast blocks, the general geometry was maintained, which is verifiable by the structural integrity of the compression only three legged vault (see figure 10). Having spent less than eight full hours fabricating the full set of nine solid plaster voussoirs is another achievement of this experiment, together with having close to zero waste of material.

A clear opportunity of improving this system is on avoiding the bulging effect in the elastic band caused by the horizontal outwards pressures caused by the weight of the casting fluid. Reducing the weight of the fluid material - by mixing lighter materials such as aerated aggregates or cork - would reduce this effect, but it might prove not desirable in every situation. Strengthening the band as to avoid its lateral deformation seems to be the solution to the problem. This can be achieved in various ways:

1. by exerting a greater traction force in the band by means of industrial machinery;
2. by using a different kind of material that stretches in its tangential direction but not in this normal, like some kind of telescopic arrangement;
3. by using additional supports along the external face of the band, materialized as pins positioned in a similar fashion as the main ones in the vertices.

Future of research avenues lie in the optimization of the fabrication system as well as diversification of scale and materials. Although there are clear advantages in the simplicity of the hole drilling for pin fixation method, it wastes board material and is time consuming. Using servomotors actuated by an Arduino style micro controller creates a closed ecosystem for variable mould casting. Another possibility relies in each pin being controlled by an articulated robot, showing advantages towards space uncluttering. Plaster was used mainly for its quick set-
ting properties. Adobe is an interesting material alternative for its availability and compression only resistance; concrete is also interesting for its resistance and durability, as well the possibility of incorporating reinforcement for other structural requirements.

This experiment shows that stereotomic research can benefit from creative approaches to its fabrication methodologies, stressing the symbiosis between project and materialization technique.

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