CORKVAULT AARHUS

Exploring stereotomic design space of cork and 5-axis CNC waterjet cutting

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Abstract. This paper presents the design, fabrication, and construction of CorkVault Aarhus, which was designed using parametric and physics simulation software and realized from ECA cork sheets cut using a CNC waterjet cutter. We recount the lessons learned through the intensive two-week workshop that explored the limits of the materials and tools through prototypes and culminated with the assembly of the final free-form vault structure. Various vaults and arch prototypes provided pedagogical and research value, building up knowledge essential to the final structure built, a human scale pavilion designed and built in three days and made of a thin shell of cork panels working only in compression. Three driving concepts were crucial to the experience: stereotomy as a supporting theory, expanded cork agglomerate (ECA) as the main material and water jet cutting as the principal means of fabrication. The complex vault shape called for precise 5-axis cuts supporting a new paradigm in building stereotomic components for architecture.

Keywords. Stereotomy; generative algorithm; digital fabrication; waterjet; cork.

1. Motivation
The Hard Co(u)r(s)e Digital at Aarhus School of Architecture is a series of workshops focused on bringing students into close contact with digital technologies, software and hardware for the purposes of architectural design research and fabrication. Connecting technology and architecture is the driving
factor of this course, and stereotomy is an architecture discipline, which has bonded these two realities from its earliest times. The need for covering larges spans with blocks of stone is a construction method that calls for technical know how and physical feasibility. On the other hand, technical power is but a part of architecture, firmitas. Technical constraints have always modelled in some way architectural expression. The ongoing relation in development of technology and free expression of form is gaining increased exposure and interest especially in regards to stereotomy principles.

Stereotomy (from greek stereos, solid + to mia, cut), is a construction technology that relies on stones which are cut to a specific shape so that, when leaned against each other, lock due to gravity and remain suspended in the air creating a vault. As a discipline, it is intrinsically connected with geometry, and with the cutting abilities of stonemasons. Algorithmic modelling allows exploration of geometries with an added level of non-standard complexity, and CNC machines make these geometries physically possible; a 5-axis water jet cutter is particularly interesting for its accuracy, speed and geometric possibilities. The experimental crossing between stereotomy as a discipline and the water jet cutter has been explored before (Kaczynski et al, 2011), but not to the extent of a finalized vault.

2. Vault Design

2.1. MACROFORM

Arches and vaults have a long tradition in architecture, dating back to Mesopotamia. The usage of ideal shapes such as the circle in vault design is an idea funded by Romans, which was only completely discarded in the 17th century with the discovery of the correlation between a hanging chain and a stress free arch design by Robert Hooke, giving way to the thinnest shell structures ever made since. With expressive shapes in his design, Antoni Gaudi set new standards in vault design with stereo-funicular models of ropes and weights.

This design method introduced by Gaudi is the basis concept used for the generation of the macro form of the vaults in the workshop we report in the present paper. The main difference from Gaudi’s method is the virtuality of all the process, contrary to the Barcelona architect’s physical models. This virtual model is built in a parametric definition, and the physics simulation is carried out by Kangaroo. The strings model adopted is a topological 4-sided grid (Fig. 1-a), which connects two opposite curves (Fig. 1-b); in each of the knots in this grid an equal force is applied. These strings act as springs, able to vary their length to a certain extent. When the simulation runs and reaches
an equilibrium (Fig. 1-c), it is presented a three dimensional representation of a mesh of ropes holding a series of weights (Fig. 1-d) or, as Hooke put it, “so but inverted will stand the rigid arch” (Block et al, 2006) - or vault, in this case. If the two opposite curves are two parallel lines, as in the opposite sides of a rectangle, we are given a catenary-shaped barrel vault. If these generator curves involve deviations from a straight line, a more complex emergent shape arises. The architect can experiment and explore various input curve forms and the algorithms enable a circular flow in which a given input develops into a form of increased complexity as is the case with genes and resulting phenotypes in living organisms. It is an automatic system, a working algorithm for designing the thrust surface (Rippmann and Block, 2012) for an ideal structure under compression (Fig. 1-e).

2.2. SURFACE TESSELLATION

A mathematically described surface does not suffice in real construction. Even if this surface is given a thickness somehow, the larger and more geometrically variable this surface, the more difficult and improbable is to build it in one single monolith. This simple fact leads to one of the key features of stereotomy: apparecchiatura (Fallacara, 2003), or the division of an architectural continuum in significant parts. Dividing a vault surface in smaller parts must meet specific requirements, other than abstractly tessellating a surface in a regular or irregular pattern. A vault, being a compression-only resistant construction, must obey to specific principles regarding the orientation of joints. On the other hand, the material and fabrication constraints, as well as intrinsic architecture geometry, govern laws of UV tessellation (Rippmann and Block, 2010).

For pedagogical purposes, it was decided to leave the tessellation grid as simple as possible and, as such, a topological grid was built on the surface. UV coordinates were informally translated as U rows and V columns, in which U were to be force knowledgeable (normal to thrust vectors) and V
would be a mere subdivision of these task bearing U rows: as Vandelvira put it, we can use joints in the most convenient fashion\(^2\); in this case we make a continuous grid with an arbitrary number of continuous divisions. The U joints are topologically parallel\(^3\) to each other, but with a variable interstitial distance inversely proportional to the U curvature of the surface (Fig. 2-a). The intrinsic curvature of the U joints was controlled in such a way that their angle with the vault opening edge would tend to a normal. This control method is a crude approximation to thrust informed joint orientation, but it does it in an efficient way in the most critical location of the vault (Fig. 2-b,c). Although this approach allows for simpler calculations, which was a key factor in the student experimentation flow within the course, some shortcomings were observed. In a non-planarised tessellation such as this, the curvature weighted U subdivision would have proved much more useful in a surface wide consideration, allowing for much more localized weighting. This would allow, for larger blocks in the planar side of the vault, creating an expressive linguistics of correlation between curvature and cell dimensioning.

*Figure 2. Left to right: (a) Curvature weighted subdivision of U lines (near horizontal ones). (b) In red, the new directions for naked edge adjacent divisions normal to thrust vectors. (c) Planar extrados resulting from subdivided cells.*

### 2.3. VOUSSOIR GENERATION

A surface subdivided in smaller cells is by no means enough to characterize a stereotomic vault. Stereotomy needs weight, and weight relates to volume. This volume, defined by the thickness of each constructive module - called a *voussoir* - has in its side faces the interface joints that allow this system to work. If the tessellation should comply with the thrust vector along the surface, it is also true that three-dimension joint surfaces should also be normal to the thrust surface at every point.

The modelling strategy for creating thickness from the gene surface relied on creating a copy of the control points that define the voussoir surface cell (Fig. 3-a), along the thrust surface normals (Fig. 3-b,c), allowing enough information for rebuilding the cell bounding curve\(^4\). Since the control points are shared by consecutive cells, a good contact surface between voussoirs is guaranteed, and a composition of voussoirs is thus achieved (Fig. 3-d, 2-c).
3. Materiality and fabrication

We now discuss cork as the main material for the vault construction and the waterjet cutting facilities.

The construction material for the vault is cork, in its expanded agglomerate form. Cork has traditionally played a part in architecture for its insulation properties, as is observable in the Convent of Capuchos in Sintra, or the Convent of Santa Cruz do Buçaco, both set in cold mountains and having a layer of cork outside doors and windows. Besides these properties, cork is also highly resistant to compression and is a strong acoustic barrier. These remarkable properties are due to the cellular structure of this material, composed of tiny pockets of air enclosed in polyhedral air-tight membranes, packed in a prismatic fashion (Pereira, 2011).

Apart from the outer layer function of cork panels, Nuno Graça Moura has used ECA blocks to build load-bearing walls. Following these experiments, and those of José Pedro Sousa (Sousa and Duarte, 2012) in which cork is machined with digital processes, Pedro de Azambuja Varela has experimented on the usage of this material for building load bearing stereotomic vaults, given the compressive resistance of cork (Varela et al., 2014). Another key characteristic of cork is its softness to abrasion, making the 100mm thick ECA boards a very interesting material for water jet cutting. The same tool was used to cut the springer foundation from 100mm thick LECA concrete blocks as well as 19mm plywood boards for vault models.

For a broader understanding of the maximum extent of cork possibilities due to its compressibility and lightness - regarding maximum span, the students performed a span proof-testing exercise in which an arch is extended in steps—this is visible in the upper left of Figure 7.

The usage of multi-axis digital tools for machining mass materials (Kaczynski et al, 2011; Fallacara, 2003) for stereotomy purposes is the contemporary manifestation of a mason’s expertise. Water jet cutting depends on a very high-pressure stream of water with an optional abrasive powder
mixed within the stream to remove material in the cutting process. The accuracy of this method is widely sufficient for architecture purposes, as the cutting trails are 1mm thick and the edges have controlled angles thanks to an algorithm, which inclines the nozzle tip to control kerf known as IKC. This inclination is possible due to the 5-axis nature of the machine, which allows for <45º angles, allowing the fabrication of slanted wall blocks in one single pass.

The nature of the process, relying on a stream of water, makes it a machine suitable only for cutting ruled surfaces. The maximum angle of the jet stream on the Idroline 1720 machine that was used in the project is 60º with the vertical and the maximum depth of raw material is 130mm, cutting all the way through. The machine is optimized to cut material wide, rigid and heavy enough that is does not move while the operation is in progress; cutting a small block is not possible as there is no practical way of fixing it. All of these characteristics hint to a very specific usage of the jet stream, which is to cut curtain-like surfaces, leaving the top and bottom side untouched. Although this clearly constrains geometric freedom, the speed and fine finishing provided are more than enough to spark the intellect in finding the best way to use these kinds of surfaces to the benefit of architecture, following a deep tradition in stereotomy. The strategy used was to make intrados and extrados planar, parallel to each other and finding the best fit to the thrust surface.

The water jet software is mainly targeted to the cutting of 2D shapes, that is, vertical cuts following an XY path. Creating a 3D cutting routine relies in specifying pairs of points, which together define a straight edge in space. Given a bottom polyline and a top polyline, the software tries to match the point pairs but fails to do so if the polyline are not topologically equivalent. Another finding is that the start and end points should match, as well as the direction of the polyline; comparable to a simple “Loft” operation.

4. Vaults construction – centring, de-centring, & springer

During one of the class sessions, students were challenged to assemble a vault having only the fabricated voussoirs made of plywood on a 1/5 scale, (Fig. 4). After giving up, this naïve exercise was clear enough to explain the importance of the centering when building a vault.

Students were given the freedom to design various centring, relying mainly in an abstract grid composed of interlocking vertical planes made of cardboard. These were designed using the intersect operation between vertical planes and the intrados for the contact contour of a continuous running vertical plane which would define one of the minimum two lines for each
vousoir intrado. The total profile of these vertical planes was obtained by subtracting the interlocking thickness of the cardboard, which was then fabricated by laser cutting.

Figure 4. Left to right: (a) Students trying to assemble a vault without centring. (b) Generation of intrado curve, finishing the necessary steps to define the vousoir. (c) Final vousoir with planar intrado and extrado and side ruled surface (d) Experiment with puzzle fitting vousoirs made of plywood.

De-centring involved the removal of the centering and is a crucial part of the construction project; various strategies were experimented, mainly driven by the scale of the model. A first try on the plywood model consisted on having the vault built on top of a base with a hole for the centering. This allows for the centering to be lowered or the whole structure including the base to be raised. A second method relied on having a sub-base under the proper centering that could be slid out below the proper centering, which was a test for the third strategy which involved a pallet jack. The jack was used for lowering the centering in the “mini-vault” construction, a small vault made of cork vousoirs. While this method proved efficient, it was clear that the area controlled by the pallet jack was too small for the final six-meter structure. Taking cues from the Free-form Catalan Thin-tile vault by the Block Research Group, the “mini-vault” was rebuilt so that the decentering would be done with the aid of cardboard softening by water hosing as shown in Figure 5.

Figure 5. (left) Cardboard centring is dampened by spraying water from a hose. (centre) Dampened centring removed carefully. (right) Small cork vault with centring removed supporting weight of a person.

In order to stabilize the base of the vault, a simple solution was developed using to handle the lateral forces. Force vectors within an ideal vault, alt-
hough two-dimensional intrinsically, are three-dimensional extrinsically. These vectors, given that the vault covers an actual span, always have a horizontal component pushing it outwards. Just as Earth’s gravity is compulsory for a vault to function, Earth’s soil is also the traditional clamping which prevents a vault from collapsing.

Given that the cobbled stone pavement should not be affected, a temporary springer was constructed from light concrete blocks held to the ground with 150mm metal poles stuck in the earth between the stones. These poles prevented the concrete from sliding horizontally, while the cork vault weight pushed them vertically to the ground. This base was built on top of 1:1 scale planes plotted in large format, providing a very accurate planning for the vault construction.

After the base was built and the centering put in place, the construction of the vault, which consisted mainly in laying cork voussoirs on top of each other (as a consistent UV grid hinted the location of the next block), took less than four hours (Fig. 6-7). Adding the time of the vault design (with a pre-built algorithm), the centering design, vault and base fabrication, centering cutting and total assembly, the whole process took three days.

![Figure 6. (left) Time lapse of the construction process, from centring to de-centring. (right) Exploded view showing the springer, centring and base blocks, and voussoirs](image)

5. Analysis and conclusion

The successful construction of a vault is historically one of the key challenges for a stonemason to achieve professional maturity. The knowledge to build stone vaults was regarded as a secret of almost mystical proportions until Philibert de L’Orme transformed it into a science, which should be accessible to all architects. On his treaty, the traits explained clearly how to successfully plan a vault structure and, following this tradition, an algorithm guided the students in this course to build vaults.
By using a lightweight material such as cork, the relation between learning hands on through handled material was kept tight, and the degree of freedom and experimentation was leveraged to a degree, which would be impossible with real stone. Besides the ease of handling due to its lightness, cork is also easy to cut within its total depth, unsurpassed only by environmentally problematic polymers. Besides these clear advantages of cork, its lightness and softness play against the very nature of vaults, which need a heavy and stable material to achieve balance. In the end, it was verified that the thickness used was enough to counter-act these negative aspects while the clear structural design kept the construction upright.

Digital technologies were one of the cornerstones of this course. The combination of digital design and digital fabrication showed its full potential. The design algorithm was tuned for the machine that produced the voussoirs, and the final construction only took three days, from initial sketch to the end of assembly. The role of digital processes was critical, and although some parts of the flow could be hand made, the time to accomplish the tasks would be unbearable within the scope of a two-week course. Speed is one of the positive aspects of digital processes as is accuracy. Stereotomy is highly dependent on accuracy, as it depends on dry joints with no mortar, and the water jet cut is brilliant in achieving that degree of perfection.

All these components were fit together in a course in which the students got direct contact with vaulting and stereotomy, building various arches and vaults with a fabrication method providing speed and accuracy at the cost of a geometry constraint, which proved an architectural expression theme.

Figure 7. (left) All the voussoirs fabricated for the final vault. (right) The final vault.

Endnotes
1. In Rhinoceros3D terminology, a curve also encompasses straight lines.
2. “Vandelvira se desinteresa por la longitud de las dovelas, diciendo que las cerchas cerra-rá por do quisieres.” (Calvo López and Alonso Rodríguez, 2005)
3. In this design, U and V curves are cartesian grid equivalent to an open 4-sided NURBS surface; in that regard we can easily establish informal analogies with parallelism, perpendicularity or cells (regions).
4. This operation occurred twice, one for each side of the surface. This contributes to having the thrust surface in the most interior possible location within the vault mass. On the other hand, this algorithm has a planar clipping strategy for compatibility with the fabrication strategy which does not modify the top and bottom side of the raw material (Fig. 3-d).
5. Expanded Cork Agglomerate board, discovered in 1893 by accident (Wilson, 2013) and produced nowadays with the help of autoclaves, is a material mainly used for architecture in-sulation, but has seen other applications to external façade finishings, since Álvaro Siza ap-plied in it in Expo 2000 Hannover.

References