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Computer-controlled fabrication of a freeform stone vault

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Abstract

This paper reports on the computer-controlled fabrication process of the individual stone blocks of the Armadillo Vault, an expressive funicular masonry vault constructed and exhibited at the 15th International Architecture Exhibition - la Biennale di Venezia. It focuses on the strategies followed to translate the digital model of the compression-only vault into a series of unique stone pieces, by addressing geometric, fabrication and time constraints.

Keywords: Digital fabrication, CNC, CAM, freeform vault, stereotomy, 5-axis stone cutting

1. Introduction

Digital stereotomy extends traditional stereotomy techniques by introducing computational methods for the design and fabrication of complexly shaped voussoirs (Fallacara [1, 2]). Such an approach is necessary to precisely cut hundreds of geometrically complex stones without spending months in the process. It also allows the geometry generated with computational tools to be transferred directly to a CNC machine by using respective machine code.

This paper describes the computer-controlled fabrication process of the individual stone blocks of the Armadillo Vault, an unreinforced, dry-set masonry vault constructed and exhibited in the Corderie dell'Arsenale for the 15th International Architecture Exhibition - la Biennale di Venezia (Figure 1). The fabrication process was carried out on a 5-axis CNC bridge saw and milling machine. The exhibited vault is a collaborative effort of the Block Research Group (BRG) at the Institute of Technology in Architecture, ETH Zurich, Ochsendorf DeJong & Block (ODB Engineering), and The Escobedo Group. The vault is composed of 399 discrete limestone voussoirs, covering an area of 75 m^2 with a maximum span of over 15 m in compression. All voussoirs are placed without mortar or other structural connection. The structural aspects of the project are described in (Van Mele *et al.* [3]); and the architectural geometry and fabrication design are presented in (Rippmann *et al.* [4]).

The paper also focuses on the strategies followed to translate the digital geometry of the vault into a series of unique stone pieces, by addressing geometric and fabrication constraints. To guarantee the correct transfer of the geometry of the voussoirs to the real stones, the geometrical interdependencies between the shape of the blocks and the physical limitations of the fabrication process were taken into account.

Figure 1: The Armadillo Vault, built in the Corderie dell'Arsenale in Venice, Italy.

Based on previous experience in using a computer-numerical controlled (CNC) subtractive cutting process for the voussoirs of an expressive funicular vault (Rippmann *et al.* [5]), new and revised fabrication strategies were developed to achieve the task of cutting all 399 pieces in just five weeks. Usually, the software setup available for translating the geometry of the voussoirs into machine code for the CNC machine controller requires the user to digitally process each voussoir separately. Due to the tight schedule and for safety reasons, other options like using macros or developing custom-made scripts for the generation of all machine code files were discarded. Instead, it was decided to develop custom scripting routines for the 3D modelling software Rhinoceros to generate reference geometric elements for each voussoirs model. These data can then be easily imported into the proprietary CAM software environment to efficiently define the cutting routines and generate the machine code. A similar workflow for processing bespoke elements for timber constructions is presented in (Stehling *et al.* [6])

This paper is structured as follows. In Section 2, the geometry of a voussoir is described. In Section 3, the machine setup and computer-aided software setup used are described. In Section 4, the constraints imposed on the voussoir geometry, by the machine setup, assembly process, time, tolerances and structural requirements are introduced. Section 5 describes the fabrication process from the generation of the individual machine codes for each stone, to the geometrical validation of the finished blocks.

2. Voussoir geometry

Each voussoir has a planar extrados surface (Figure 2a). The intrados surface of the voussoirs is doubly curved. It is created with parallel cuts by a circular blade leaving fins that are subsequently hammered off (Figure 2b). The primary load-transferring side faces (the surfaces aligned in the course direction) are ruled surfaces (Figure 2c). They are cut with a cylindrical profiling tool that creates the (male and female) notches (Figure 2d,e). These male/female notches served primarily as registration marks during assembly. The non–load-transferring side faces (the surfaces perpendicular to the course direction) are also planar surfaces (Figure 2f). For structural reasons, load-transferring side faces had to be flush and therefore precisely cut. In contrast, both intrados and extrados surfaces do not require the same level of precision.

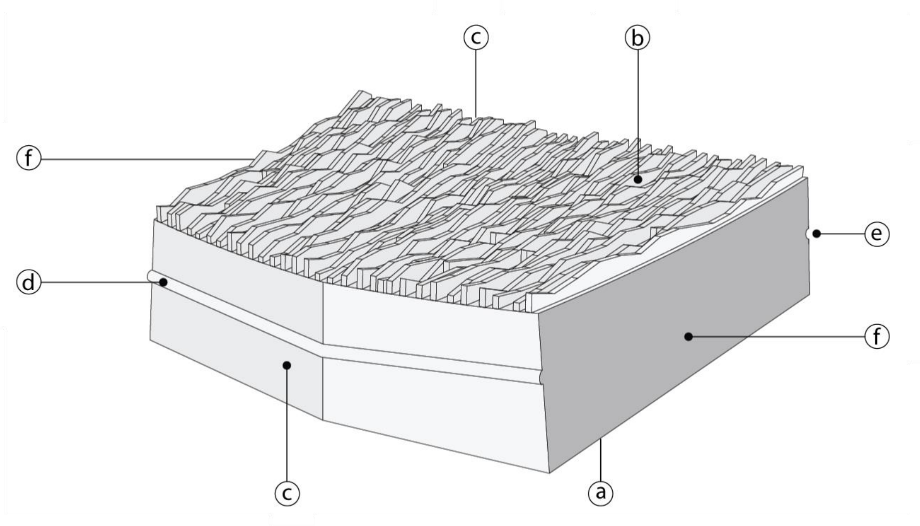

Figure 2: Voussoir parts: (a) extrados; (b) cutting pattern on intrados; (c) load-transferring side faces; (d) male notch ridge; (e) female notch groove; and (f) non-load-transferring side faces.

3. Fabrication setup

Three different types of CNC machines were used throughout the entire machining process to shape rough blocks, just extracted from the quarry, into finished bespoke voussoirs. A 2-axis Pellegrini Single-Wire Saw CNC machine is used for cutting rough limestone blocks to dimensioned work slabs. These are then cut transversally and longitudinally according to predefined blank sizes using a 3-axis Park Industries Predator blade-saw CNC machine. The volumes of the blanks are reduced to 55 different sizes, defined by the aligned bounding boxes of the corresponding voussoirs. This clustering strategy helped to save time and material during the fabrication of all voussoirs. Finally, for the finishing of the actual voussoir geometry, a 5-axis OMAG Blade5 NC900 CNC machine is used. This paper focuses on this last stage of the cutting process. This section provides a detailed description of the CNC machining and software setup used throughout the fabrication process.

3.1. Machining setup

3.1.1. 5-axis CNC bridge saw and milling machine

The OMAG Blade5 NC900 bridge saw is a 5-axis CNC machine, specifically designed for stone cutting or milling (Figure 3). The machine is composed of three linear axes X, Y, Z, and two rotational axes B, and C. A steel cutting table serves as a platform to place and securely mount the stone blanks. The milling head has a range of 440 cm along the X axis, 305 cm along the Y axis, and 200 cm along the Z axis, and can rotate from 0° to 360° around the C axis. The spindle can rotate +/- 140° around the B axis when the large circular blade is not mounted, otherwise it is automatically limited to -25° to 90°. To prevent fast and excessive tool wear, the spindle head is equipped with water jets, which eject water while the tool is in contact with the stone. This prevents the temperature of the tool to increase and also cleans the cutting area from stone sediment. The machine is controlled by a Siemens SINUMERIK 828 CNC controller, which allows the machine to be controlled using respective machine code.

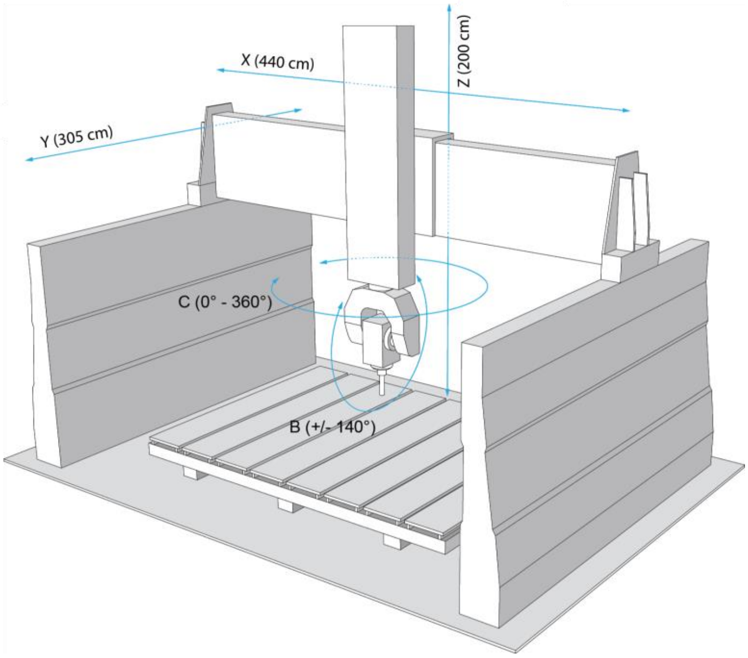

Figure 3: Diagram of the OMAG Blade5 NC900 5-axis CNC machine with all axes marked

3.1.2 Tools

A standard diamond-coated circular blade (⌀ 81 cm) is used to cut the side faces and the rough cutting pattern of the intrados. Custom-made diamond-coated profiling tools were designed to finish the side faces of each voussoir. A cylindrical tool with a 12 mm diameter semi-circular ridge is used to cut faces with a female registration groove (Figure 4a), and one with a 12 mm diameter semi-circular groove for the faces with a male notch (Figure 4b). A plain cylindrical tool is used to finish faces where no registration notch is needed (Figure 4c).

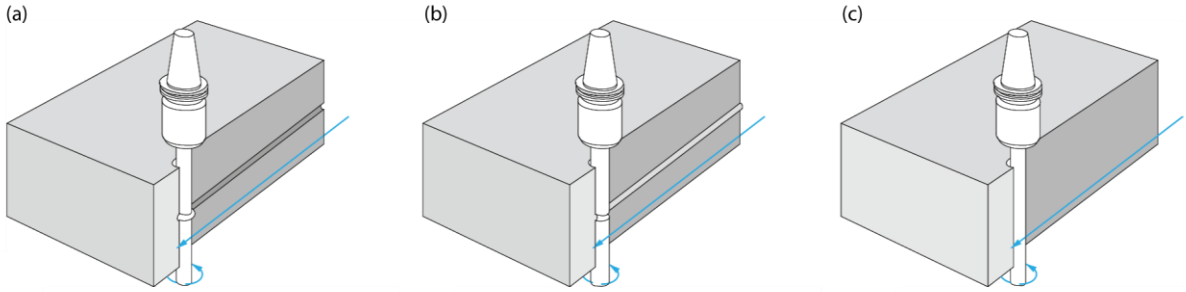

Figure 4: Custom-made profiling tools: (a) female registration-groove tool; (b) male registration-groove tool; and (c) plain cylindrical tool.

3.2. Software

The CAM-software EasySTONE (Version 4.9) was used to digitally process the stone parts, and to generate machine code for the SINUMERIK 828 CNC controller. Working with this CAM software, one usually defines fabrication features based on reference geometric elements manually generated in the program, and subsequently associates these elements to predefined sets of tools and machining strategies. Because of a tight schedule and for safety reasons, it was not feasible to develop and use macros to automatically generate machine code. Instead, a semi-automated parametric strategy was used to generate the machine code for all voussoirs of the vault, using reference geometric elements for each voussoir model. Custom scripting routines were defined to generate these reference geometric elements for every part of each voussoir model. This strategy will be discussed in more detail in Section 5.

4. Fabrication constraints

The design of the vault and its individual pieces was entirely driven by constraints related to the fabrication process and to the architectural and structural requirements and timeline of the project. This section, discusses the fabrication constraints in more detail.

4.1 Machining constraints

The shown voussoir geometry was processed using two different types of tools. The tools used for the machining process constrain the shape of the resulting voussoirs. The circular blade only allows cuts for which the blade is constrained to a plane (Figure 5a). Because of this, the cuts for the fins of the intrados needed to be defined in the digital model as planar surfaces. An additional constraint is that the minimal inner curvature of the intrados of each voussoir, has always to be bigger than the radius of the blade. To avoid self-intersections with the trajectory of the blade, all side faces of the voussoir are convex. Unlike the circular blade, profiling tools allow ruled surfaces to be cut (Figure 5b). Because of this, all non-planar side faces need to be defined in a way that can be described by moving a generator line in space.

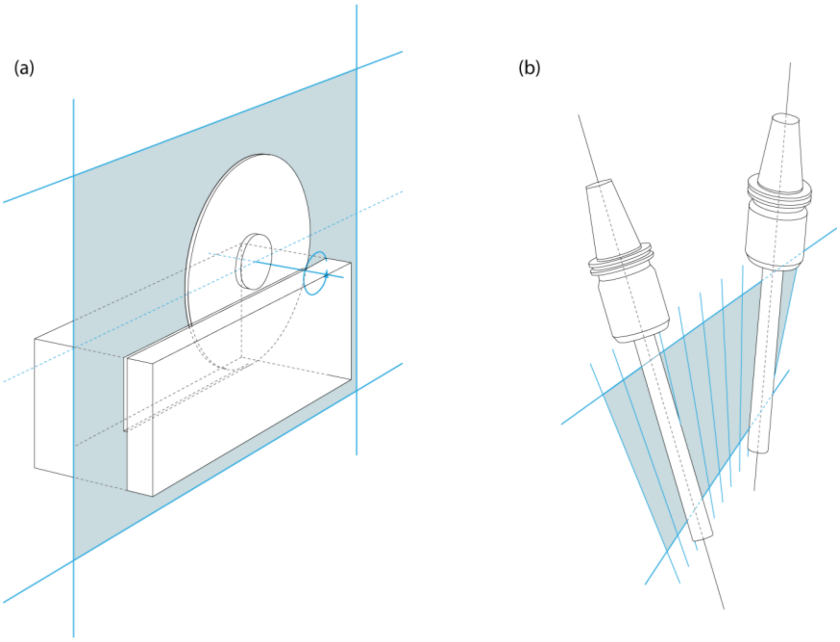

Figure 5: Surface shapes possible depending on the tool used for the machining process; (a) Circular saw blades cuts are constrained to planar surfaces; and (b) Profiling tool cuts are constrained to ruled surfaces.

The way how the blanks are placed on the cutting table constraints which and how faces are cut. In most cases, during the subtractive process of three-dimensional pieces, flipping and re-referencing the workpiece is needed. Due to the complexity of this reorientation process, such manipulations of workpieces add time to the machining process and may cause tolerance issues. Hence, all voussoirs are designed such that all their extrados faces are planar surfaces.

Even though profiling tools allow to cut ruled surfaces, the machining time increases between 5 and 10 times, compared to the blade cutting (Rippmann [7]). Therefore, the use of these profiling tools is constrained to where it is strictly necessary. This means that just side faces are cut using profiling tools. Because these profiling tools can only remove a maximum of 3 mm of material on each pass, several passes are needed to reach the final doubly curved shape. For this reason, a best-fitting, planar approximation of every final doubly curved shape is first cut with the circular saw blade. The doubly curved intrados is roughly approximated using side-by-side cuts.

4.2. Notch constraints

The use of profiling tools to cut the notches on the load-transferring side faces constrains the way how the machining paths for these tools are defined. Two constraints need to be considered to meet with tolerance and structural requirements. First, the profiling tool should always be aligned with the generators of the ruled surface. Second, every notch should be placed with a minimum distance of 1.8 cm from the edge, to avoid spalling. All ruled surfaces are trimmed on their upper and lower parts by the intrados surface and extrados surface respectively. The generators are not always perpendicular to the top and bottom directrices of the surface. Because of this, especially for thin voussoirs, some machining paths can lie too closed to one of the edges of the face. To avoid this, all machining paths are defined in such a way that they meet with the second constraint while they are as perpendicular as possible to the generators of the surfaces.

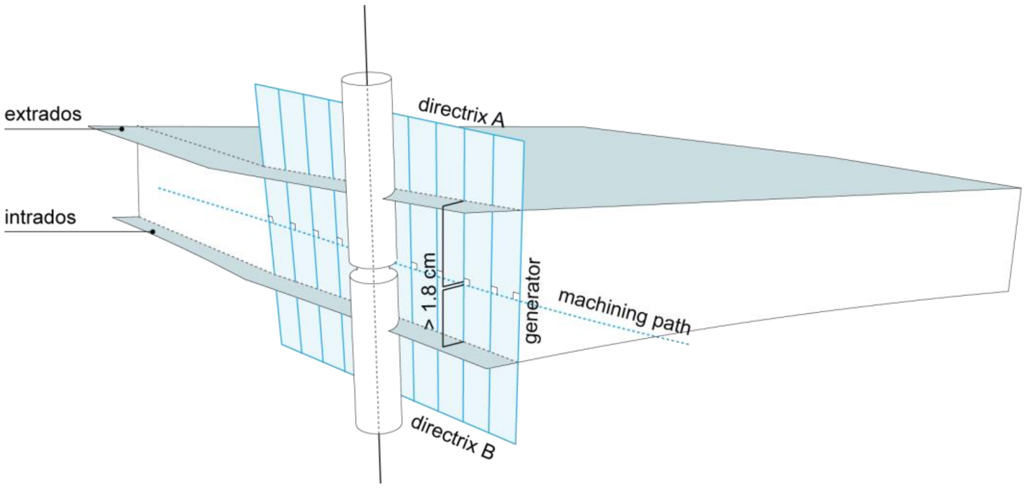

Figure 6: Doubly ruled surface constraints define the machining path of a profiling tool.

5. Method

The geometry of each voussoir was digitally processed and machine code was generated for CNC machining. The stones were cut using a 5-axis CNC machine to achieve a result that meets the high precision requirements and the desired finish, while keeping to a very tight schedule.

5.1. Digital processing

The machine code of each voussoir is generated using the CAM-software EasySTONE (Version 4.9), after importing its cutting geometry from Rhinoceros. This imported geometry contains the surfaces that define the shape of the voussoir and additional reference geometric elements used to define respective machining paths. Best-fitting, planar surfaces are generated on each side face, to define cutting trajectories for the saw blade (Figure 7a). The normal and bottom edge of these surfaces define the direction and location of the cutting trajectory. The side-by-side cutting pattern on the intrados (Figure 5f) is defined by a series of surfaces, which are used to define the orientation of the blade, and the direction of the cuts (Figure 7b). To improve the visual appearance of the pattern formed by the leftovers of the fins, the lead-in and lead-out paths of the circular blade were locally controlled to create shallower, intermediate cuts at specific locations on the intrados (Figure 7c). Doubly ruled surfaces, are used to define the machining paths for the load-transferring and non-load transferring side faces of the voussoirs.

The generator and the normal of the surface on each point along the edge, define the direction, orientation, and position of the profiling tool (Figure 7d).

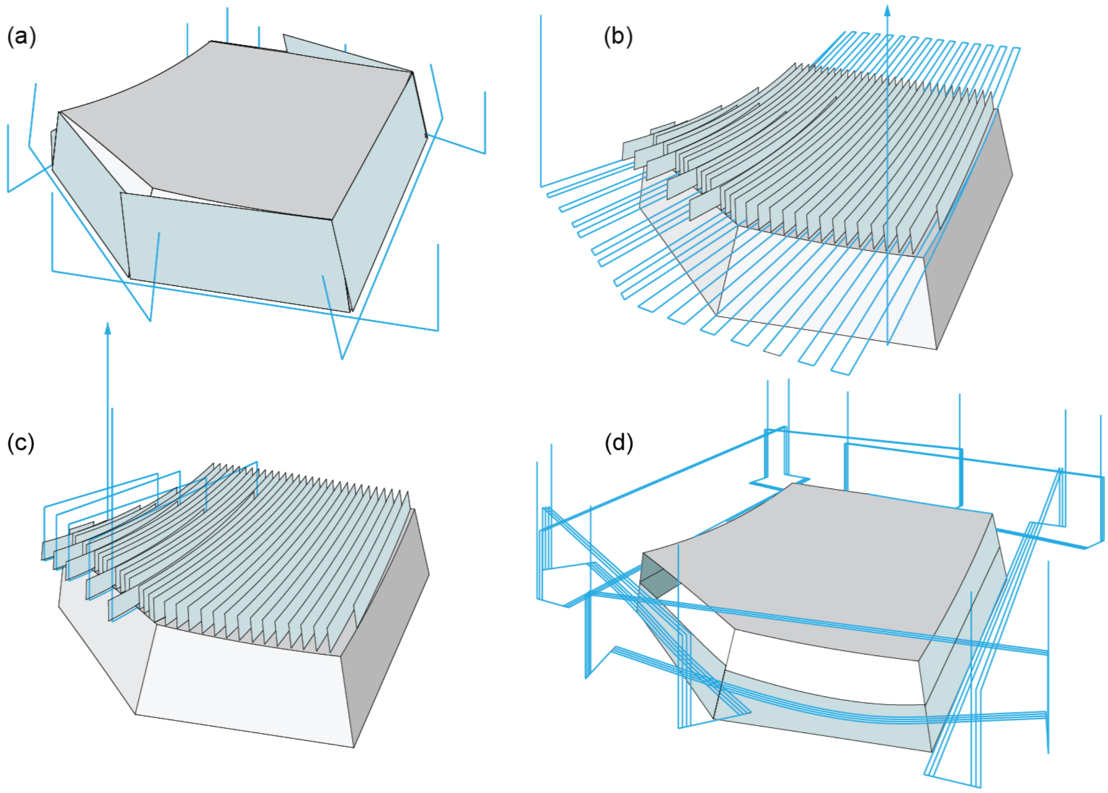

Figure 7: Machining trajectories defined using reference geometric elements for a typical voussoir: (a) best-fitting, planar approximation of the final side faces; (b) side-by-side cutting pattern on the intrados; (c) intermediate cuts at specific locations on the intrados; and (d) side faces finishing passes

5.2. Cutting process and machining sequence

The final stage of the cutting process for each voussoir is done with the 5-axis CNC machine. Two cutting areas are defined on the cutting table of the machine in order to save time by replacing an already finished voussoir in one cutting area while the next stone is being processed in the other area. Each blank (Figure 8a) is precisely held in position and spaced apart from the cutting table using several vacuum pods. Once the blank is positioned in one of the cutting areas, the side faces are pre-cut using the circular blade (Figure 8b). The result is a best-fitting, planar approximation of the final side faces (Figure 8c). Subsequently, the saw blade is also used to process the top face of the blank, which corresponds to the intrados of the vault, by a series of side-by-side cuts (Figure 8d). To save time, the saw changes the direction of its trajectory each time it finishes a cut, tracing a zig-zagging path. Then, the fragile fins that result from the gap left between cuts, are knocked off manually (Figure 8e).The preprocessed side faces are finished using the appropriate profiling tool, as discussed in Section 3.1.2 (Figure 8f). To minimise possible tolerance issues caused by small imperfections in the calibration of the machine, all side faces are processed in the same direction relative to the machine head orientation.

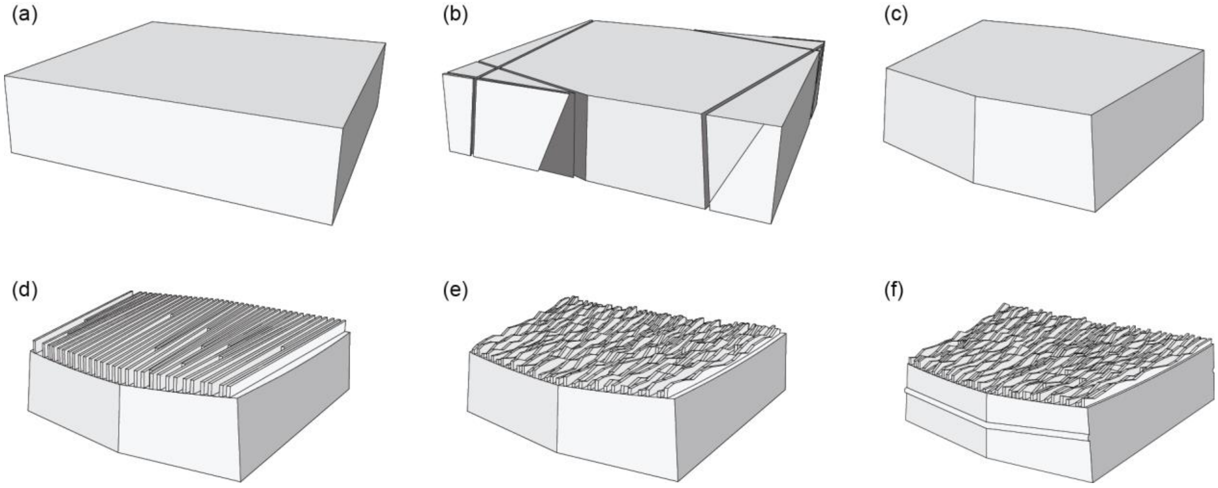

Figure 8: Machining sequence illustrating the cutting for a typical vault voussoir: (a) blank; (b) side-face pre-cuts; (c) best-fitting, planar approximation of the final side faces; (d) side-by-side cutting pattern on the intrados; (e) knocked-off cutting pattern on the intrados, and (f) side faces processed with custom-made profiling tools

5.3. Validation

Measuring tapes were used to validate the dimensions of each voussoir. The finished voussoirs were only accepted if the deviations were within 0.75 mm. In case that the deviations were larger than 0.75 mm, a new voussoir was cut. On average, one voussoir out of 25 needed to be discarded and re-cut. Every 20th finished voussoir was scanned in order to compare its geometry with the corresponding digital model, using the software CloudCompare. This check was done to verify if the calibration of each axis of the machine was accurate enough to meet the required tolerances.

6. Conclusions

This paper presented a fabrication method to achieve the task of cutting 399 unique stone voussoirs over a timespan of only five weeks. A machining strategy was developed to be able to fulfil the aforementioned task, by addressing geometrical, fabrication, and time constraints. In addition, a strategy was developed to efficiently translate the digital geometry of the vault into a series of machine-code files, to control a 5-axis CNC machine, within a maximum tolerance of 0.75 mm.

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The Armadillo Vault is the centrepiece of the exhibition “Beyond Bending - Learning from the past to design a better future” for the 15th International Architecture Exhibition – La Biennale di Venezia, curated by Alejandro Aravena. The structure is the result of an intensive collaboration between the Block Research Group, ETH Zurich, Ochsendorf DeJong & Block (ODB Engineering) and The Escobedo Group. The presented process was heavily influenced and informed by each team’s experience and expertise, previous collaborations and many discussions.

Full credits Armadillo Vault:

Structural design & Architectural geometry: Block Research Group, ETH Zurich - Philippe Block, Tom Van Mele, Matthias Rippmann, Edyta Augustynowicz, Cristián Calvo Barentin, Tomás Méndez Echenagucia, Mariana Popescu, Andrew Liew, Anna Maragkoudaki, Ursula Frick, Nick Krouwel

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Sponsors: Kathy and David Escobedo, ETH Zurich - Department of Architecture, MIT - School of Architecture + Planning, NCCR Digital Fabrication, Pro Helvetia, Artemide

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