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Optimising Stone-Cutting Strategies for Freeform Masonry Vaults

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Summary: This paper reports on recent developments for the computer-controlled fabrication of individual stone blocks of a freeform masonry vault in Austin, TX, USA. Based on structural requirements, state-of-the-art, 5-axis stone-cutting processes and software solutions used in the stone industry, new methods were developed to optimise the block geometry and machining strategies for this structure. A customised software program was written to simplify part preparation, reduce machining time and extend known fabrication procedures in a flexible and streamlined setup.

Keywords: *Digital Fabrication, CNC, CAM, freeform vault, unreinforced cut- stone structure, stereotomy, form finding, 5-axis stone cutting*

1. INTRODUCTION

This paper reports on recent developments for the demanding stone-cutting process of the MLK Jr. Park Stone Vault in Austin, TX, USA, (Fig. 1).

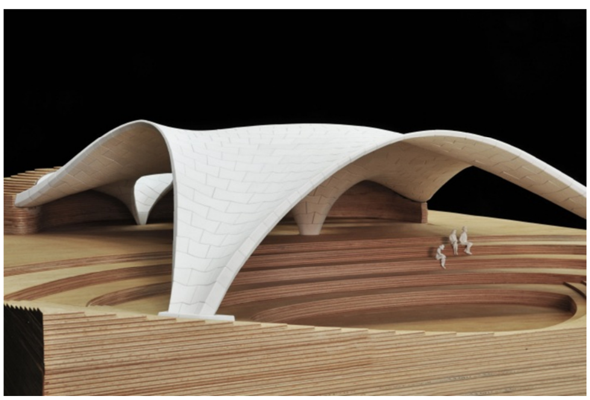

Fig. 1 3D-printed structural model of the MLK Jr. Park freefrom unreinforced masonry vault in Austin, TX, USA

The research presented in this paper enters into the relatively new research field of digital stereotomy [1, 2]. Digital stereotomy revisits and extends traditional stereotomy, the art of cutting up stone blocks or dimensioned work pieces into discrete voussoirs [3] by introducing computational strategies for the design and digital fabrication of the complex voussoirs for this "freefrom" masonry vault, addressing structural requirements and fabrication constraints [4]. The MLK Jr. Park Stone Vault, with a maximum span of 28 m, will cover a 600 m^2 multi-purpose community and performance space. The on-going planning process of the structural stone vault served as a case study to analyse and further develop existing fabrication processes for its complex voussoir geometry. The planned realisation of this radical stone structure requires a highly streamlined process to guarantee a feasible and efficient production. The following requirements were identified and addressed during our research:

- geometry optimisation of the voussoirs based on specific structural requirements and fabrication constraints,
- reduction of time to digitally prepare the machining process,
- reduction of machining time per voussoir,
- optimisation of tool pathing to achieve defined groove patterns, and
- improving the efficiency of work piece referencing techniques while guaranteeing sufficient precision throughout the cutting process.

Based on the analysis of existing, state-of-the-art, computer-numerical-controlled (CNC) subtraction processes used in the stone cutting industry, it was clear to the authors that available solutions do not meet these requirements [5]. Hence, revised and new fabrication strategies were developed to improve the feasible production of individual, complex voussoir geometry for this freeform vault.

Considering the constraints of the well-established, fast and flexible 5-axis circular-blade cutting process, specific geometric modifications were applied to the voussoir geometry. This was done using iterative optimisation strategies mainly addressing the planarization of the cut surfaces [4].

Available software solutions require the user to model and process each voussoir of the vault individually to generate the necessary tool path data. Consequently, this tedious process using different applications (modelling & tool path generation), was combined and automated in a streamlined procedure by customised scripting routines [6] in the 3D modelling program Rhinoceros® [7]. The highly improved flexibility of this approach was used to adaptively control the feed rate of the CNC process according to the cut geometry, which can significantly reduce overall machining time. The flexible setup was further used to generate customized tool path strategies to match specific groove patterns based on design aspects and economic considerations.

Due to the complexity of the voussoirs and the machine limitations, all parts need to be processed from two sides demanding a manual flipping and re-referencing of the voussoir during the production. New part handling and reference strategies were developed to overcome possible tolerance problems of this process.

The developed methods were refined and tested on an OMAG Blade5 NC900 CNC machine at AX5 Resources, TX, USA (Fig. 2). Several mock-up voussoirs of the vault were digitally and physically processed and evaluated using the described setup; generating valuable data for first feasibility studies concerning production time and costs for the stone cutting process of MLK Jr. Park Stone Vault and freeform masonry vaults in general.

Fig. 2 Stone cutting process on an OMAG Blade5 NC900 CNC machine at AX5 Resources, TX, USA

This paper is structured as follows. The next section summarizes the main objectives of this research. In Section 3, the relevant machine setup and computer-aided manufacturing (CAM) software setup available at AX5 Resources are described in detail and evaluated. Section 4 elaborates on the methods used and developed addressing the automation of the CAM process and the machining strategies. Section 5 illustrates how these methods were used to digitally and physically process several mock-up voussoirs and discusses these results. Finally, Section 6 concludes the research presented in this paper.

2. OBJECTIVES

The key objective of this research is to streamline the process for the production of hundreds of individual voussoirs of the MLK Jr. Park Stone Vault and other comparable freeform stone structures. The development of state-of-the-art cutting processes in the last two decades has been mainly driven by the need to process unique and geometrically complex objects such as sculptures, handrails and ornamental surface reliefs. Processing these very specific objects in addition to carrying out day-to-day, routine jobs such as kitchen toppings requires an extremely flexible machine and software setup. As a result and due to the low level of CAM automation features, these setups lack efficiency concerning the processing of a high number of similar but geometrically unique voussoirs as used for the MLK Jr. Park Stone Vault. Consequently, these voussoirs would usually be processed separately as individual complex forms, causing a high demand for digital modelling and CAM preparation, which will significantly increase fabrication costs.

Therefore the key objectives of this research are to

- reduce the time to digitally process the voussoir geometry, and
- evaluate the most feasible cutting and tooling strategies, while
- minimising cutting time and tool degradation.

3. HARDWARE AND SOFTWARE SETUP

Escobedo Construction owns several CNC stone-cutting machines. A 2-axis CNC diamond wire saw is used for cutting stone blocks to dimensioned work pieces, which are either processed manually or further machined using the 5-axis CNC router of AX5 Resources. This research focuses on the use of and control over the 5-axis router OMAG Blade5.

3.1. Machining Setup

The 5-axis, portal router OMAG Blade5 (Generation 3) is a customised CNC machine setup, featuring five axes X, Y, Z, C and B, as illustrated in Figure 3.

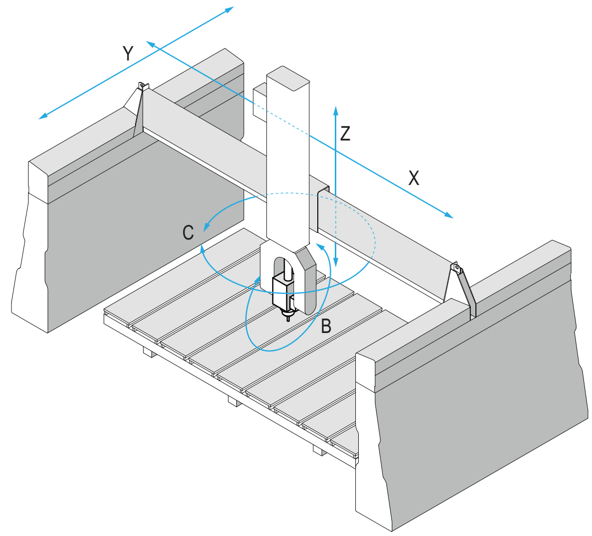

Fig. 3 5-Axis router OMAG Blade5 (Generation 3) with marked axes X, Y, Z, C and B

The machine has 440 cm of linear movement in X-direction, 305 cm in Y-direction and 200 cm in Z-direction. The rotational axis C is free to rotate within 0° to 360° and axis B is limited to +/- 140°. The range of Axis B is automatically limited by the NC to 90° to -25° by a sensor when either of the large circular blades housings is attached to the spindle. The table dimensions within which the work piece is positioned are 426.7 cm x 245.1 cm. A gantry crane is installed in the workshop to lift heavy work pieces on and off the table.

The machine is controlled via a SINUMERIK 828 CNC controller [8] by operating it manually or by importing ISO G-code [9] extended with controller and machine specific extensions and variations.

In general, the movement along or around each axis is numerically controlled by defining corresponding length, respectively angle settings. This numerical data can be passed on to the machine line by line using ISO G-code, which operates on a relatively simple syntax, as shown in the following basic sample code snippet:

```
...
N24 G0 C40 B90
N25 G0 X4.3773 Y2.0078
N26 G0 Z18.0814
N27 G1 Z8.1 F200
...
```

These four lines (N24 to N27) represent a small, very basic part of a G-code file to process a voussoir using e.g. a circular blade. `G0` stands for rapid positioning and moves each axis at its maximum speed until its defined position is reached. In our example, this means that first axis C and B rotate simultaneously to reach their defined angle positions at 40° and 90°, respectively. Subsequently, in line N25 and N26 the axes X, Y and Z are moved to their defined coordinates. Line N27 is specified with `G1` to set the program in coordinated motion mode during a cutting procedure, enforcing an interpolated straight movement including all axes. The feed rate is defined to 200 cm/min, set with `F200`.

3.2. Computer-Aided Manufacturing (CAM) Setup

Conventionally, the CAM-software EasySTONE® (Version 4.8) [10] is used by the professionals at Escobedo Construction for the digital processing of stone parts, and to export the G-code for the actual stone-cutting process. The digital workflow within the company is based on Autodesk Inventor® [11] to generate and/or prepare the geometry, followed by importing the geometry in EasySTONE® to layout the tool pathing, and eventually exporting the G-code. This digital chain guarantees the flexibility needed to process stone parts with different demands regarding complexity and precision. However, this flexibility is at the expense of a poorly streamlined and non-automated digital setup. Specifically, the lack of automation triggered the development of a new, customised CAM setup (see Section 4.1).

3.3. Setup Testing

Depending on the desired smoothness of the surface, three-dimensional parts are usually processed using several passes and tools. Tests have shown that milling strategies using several milling tools are appropriate for detailed, complex objects with high local curvature and high standards for the surface smoothness.

Our objectives are based on the processing of large, low-curvature voussoirs with different demands concerning the smoothness of individual surfaces. A typical vault voussoir has low-curvature, mainly convex top and mainly concave bottom surfaces, and several contact faces. The latter, once assembled, transfer the thrusts from one stone to its corresponding neighbours. The smoothness of the top and bottom surface is mainly driven by aesthetic considerations. In contrast, the structural behaviour and precise erection of the vaulted structure is directly related to the smoothness and accuracy of the contact faces. Optimisation strategies applied to the geometry of the voussoir as described in [4] have shown that most contact faces (>95% for the shown tessellation of the MLK Jr. Park Stone Vault) can be planarised without losing the tessellation properties. As a result, these faces can be processed with a single cut using the available large circular blade (with a diameter d of 139.7 cm). Depending on the voussoir geometry, this optimisation step can reduce machining time for the contact faces by the factor 10 compared to successive surface milling, but more importantly it allows to control the tolerances best. Correspondingly, the top and bottom surface can be processed using the circular blade by successively cutting parallel grooves to approximate the doubly curved surfaces. A smaller step size of the individual cuts (smaller than the blade thickness) results in a higher surface quality. A larger step size (larger than the blade thickness) shortens fabrication time but demands a post-processing step to manually remove the leftover material. The latter approach is advantageous because the removed pieces can be disposed separately, can be recycled as aggregate for other applications, and do not add to the sediments of the drainage system, which saves time and costs. The resulting rougher surface can relatively easily and efficiently be smoothed manually.

Processing all surfaces of one voussoir with the circular blade is preferable as the large blade cannot be changed automatically using the tool change setup of the machine. A manual tool change of the blade between two jobs would add approximately 20 minutes to the fabrication process for each side (top and bottom surface) of the voussoir. Therefore, the machining strategies presented in this paper, focuses on the exclusive use of the circular blade. Its use fosters time-saving machining strategies by sawing off large stone parts in one piece rather than successively milling away material, converting it into polluting stone dust. The limitation that for concave surfaces the local radius of curvature cannot be smaller than the radius of the circular blade has no effect on processing the low curvature voussoirs examined in our research.

The three-dimensional parts need to be machined from two sides (top and bottom surface). In early tests, "bracket parts" (Fig. 4) remain on the work piece during machining to re-reference and re-position the partly processed stone after flipping it on the opposite side.

Fig. 4 Stone-cutting process of a partly processed work piece using remaining "bracket parts" to re-reference the stone after flipping

The re-referencing often results in an inaccurate positioning of the partly processed stone due to limitations of manual measurement techniques (by tape measure). It became apparent, that in order to achieve precise machining of geometrically accurate voussoirs, an alternative referencing strategy would be required (see Section 4.2). The option of scanning has not been introduced.

4. METHOD

The previous tests and explorations have shown that the CAM setup can be further streamlined using customised automation strategies. Furthermore, it became clear that stone-cutting processes based on the large circular blade are most promising considering the research objectives and machine setup. The following sections will elaborate on the used and developed methods to address these aspects.

4.1. Software Approach

Using a tailored setup to specifically process the individual voussoirs, which are all based on similar geometry rules, has great potential to increase the efficiency of the process. Three scenarios were considered to streamline the production chain from digital voussoir geometry processing to CNC fabrication:

1. Voussoir Geometry → RhinoPython™ Geometry Scripting → EasySTONE® → G-Code → Machining
2. Voussoir Geometry → EasySTONE® Macro and Scripting → G-Code → Machining
3. Voussoir Geometry → RhinoPython™ Scripting → G-Code → Machining

In Scenario 1, Rhinoceros®, together with customised scripting methods, is used to automate the geometry processing of the voussoir. This would allow for the automated generation of three-dimensional CAD objects, such as guiding lines and surfaces, to facilitate the tool path planning in EasySTONE®. Eventually, this option was discarded due to the tedious, remaining workload for the user to define and create work piece position, alignment and tool path strategies.

Scenario 2 was not further investigated due to the poor documentation and limitations of the macro and scripting possibilities within EasySTONE®. Therefore, the idea to automate the existing setup without introducing new software packages was quickly discarded.

Eventually, the very light process chain outlined in Scenario 3 was identified as the most suitable approach for the research objectives. It combines the modelling part (Autodesk Inventor®) with the CAM part (EasySTONE®) by replacing both costly and heavy software packages with the CAD software Rhinoceros®, but enhanced with custom program parts, using its internal scripting methods for advanced automation, and additional features. This setup facilitates the tool pathing, features the simulation and analysis of the cutting procedure, and the G-code export for the 5-axis portal router OMAG Blade5.

The described approach allows for the most flexible setup to customise, automate and batch the generation of G-code files for a high number of individual voussoirs of the stone vault in short time. Interchanging files between different programs becomes obsolete because all preceding modelling and automated geometry processing for the form finding and tessellation of the vault is done in or through Rhinoceros® [4, 12, 13]. Using this integrative setup furthermore guarantees a high level of automation because data related to the generation of the voussoir geometry (e.g. identifying geometry parts such as top, bottom and contact surfaces) can easily be passed throughout the steps of automation. As a result one could theoretically process the CAM procedure for almost all voussoirs without the need of any user interaction. In our first, prototypical software setup, we used an intermediate simulation step to visualize the cutting procedure inside the Rhinoceros® viewport for each voussoir processed.

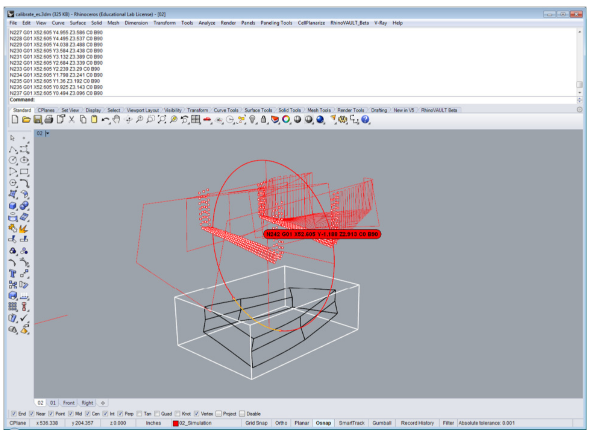

Fig. 5 Simulation animation of the cutting procedure within Rhinoceros®

A further advantage of the presented method is the possibility to add certain features that are not part of the EasySTONE® software package. This includes, for example, automated positioning of reference cuts, detailed, adaptive feed rate control, and non-parallel, converging cutting patterns, as will be further discussed in Section 5.

4.2. Fabrication Approach

The re-positioning of the partly processed work piece using "bracket parts" as described in Section 3.3 does not meet the precision requirements (approx. +/-1mm) needed regarding the research objectives. Specifically, the guaranteed flush alignment of the contact faces of neighbouring voussoirs within the tessellation bond demands the development of a new strategy using precise re-referencing techniques. The key considerations for this strategy were that

- the re-referencing stone features need to be part of the top and/or bottom surface (surfaces with lower precision requirements)
- referencing features must be precisely defined via the customised CAM setup and machined using the same CNC machine setup that is used for the part processing; and
- the tool to machine the referencing features must be exclusively the circular blade.

The machining sequence in Figure 6 illustrates the developed cutting strategy for a typical vault voussoir, which includes a new re-reference technique. The processing of the work piece starts with its positioning on the machine table, which needs to be referenced based on the defined machine, respectively part origin. Usually, the work piece from which the individual voussoir is carved out, is about 5 cm larger in all dimensions. This means that the first positioning has lower precision requirements. Once the work piece is mounted on the table, the first pass of successive parallel grooves approximates the doubly curved top surface of the voussoir (Fig. 6a). Depending on the step size of these cuts, leftover material needs to be removed manually (Fig. 6b). The three larger remaining stone parts provide space for the re-referencing cuts (Fig. 6c). These cuts cross in six points that are precisely defined in three-dimensional space based on the coordinate system of the CNC machine. Therefore, their positions are known in reference to the partly processed work piece. After processing the six planar top contact faces of this test voussoir (Fig. 6d), the work piece is flipped using the gantry crane (Fig. 6e). A steel rack, which is precisely positioned on the machine table, is used to re-reference the partly processed stone. The cross-like steel pins, together witch the reference cuts, only allow for one unique orientation and alignment of the work piece (Fig. 6f). Assuming that the steel rack has been precisely mounted on the table in relation to the machine coordinate system, the former underside of the work piece can now be precisely machined from the top, forming a perfect transition to the previously cut surfaces (Fig. 6g-j). Consequently, the machined voussoir is removed from the rack to make room for the next work piece to be processed (Fig. 6k). Finally, the leftover reference part needs to be removed manually (Fig. 6l).

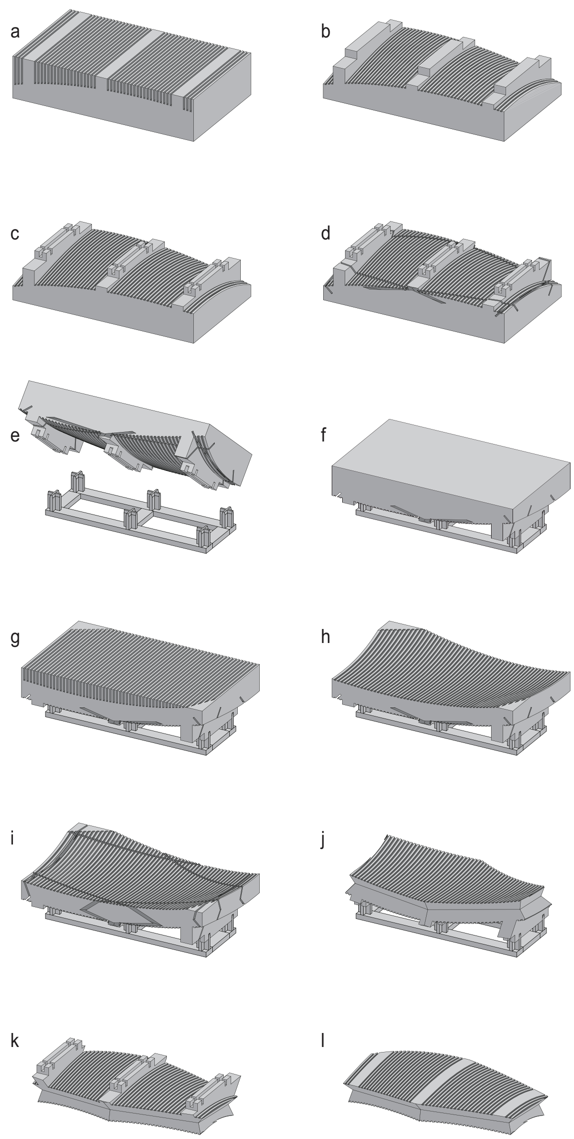

Fig. 6 Machining sequence illustrating the cutting and re-referencing strategies for a typical vault voussoir

5. RESULTS

In a two-week period, a prototypical software setup was developed and tested at Escobedo Construction. A 1/3-scaled prototype of three neighbouring voussoirs was cut on the OMAG Blade5 using the machining and cutting strategies developed. The results of these tests are shown in this section.

5.1. Software Results

The customised software setup was written in RhinoPython®. It features the customised tool pathing, based on straightforward vector transformations, to calculate the machine axes' coordinates and angle positions for a user-defined tool path step size. Surfaces to be processed are automatically identified or selected by the user to successively apply the corresponding tool path strategy (parallel vs. converging cuts, reference cuts, planar cuts). Trigonometric rules were identified to control the rotational axes without violating the given angle limitations and the sequencing of cuts. Based on the machine-specific coordinate system, the G-code is generated and exported with controller-specific code extensions (Section 3.1).

Due to safety and time saving reasons, the exported G-code files were consequently tested using simulation techniques. Small syntax changes on the G-code files made it possible to import these files into the PowerSIM application of EasySTONE® to visualize the virtual cutting process on the 5-axis CNC router OMAG Blade5. This helped to calibrate and debug the customised software setup and led to the implementation of a similar simulation environment within the Rhinoceros® display engine.

Besides collision detection and process control, usually these simulation techniques help to estimate the tool path length and cutting time. Since these numbers are highly important for the research objectives, a key aspect of the software development was to guarantee the full control over relevant parameters such as cutting volume per minute. Figure 7 illustrates a typical tool path layout for cutting the top surface of a sample voussoir.

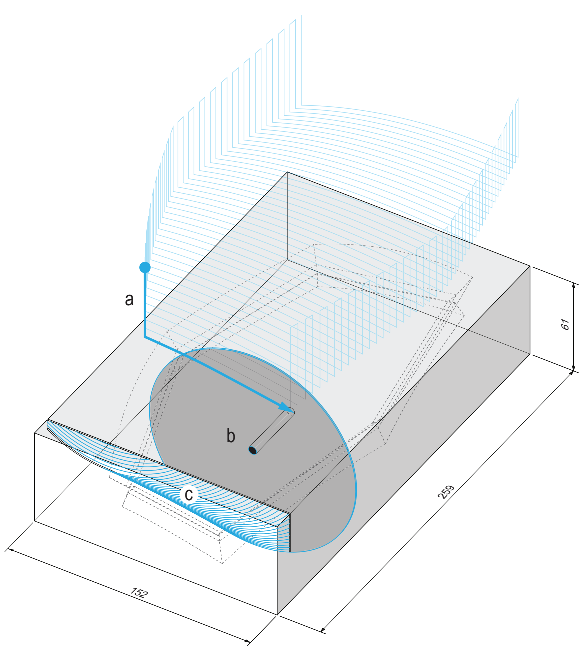

Fig. 7 Tool path layout for cutting the top surface of a sample vault voussoir generated with the customised software setup

The marked polyline (Fig. 7a) indicates the already processed part of the cutting process, respectively the tool path that the circular blade (Fig. 7b) has already covered. Figure 7c shows the varying circle segments, which represent the part of the blade edge used to cut the stone, when the tool path is followed. This value is calculated during the simulation process and serves as a measure for the maximum, local feed rate.

From experience, the volume that can be processed using this machine setup and material ("Texas cream", a soft limestone), was defined to a maximum of 4097 cm³/min. For example, based on this value and the used circular blade, with a thickness of 0.92 cm and a diameter of 139.7 cm, the process for cutting a 10 cm deep and 100 cm long groove would take 13.47 s. The feed rate would thus be 445 cm/min. Standard G-code, as exported from EasySTONE®, only defines the feed rate for rapid movement (when outside the user defined "safety distance" from the work piece), the feed rate for plunging into the material, and the actual cutting feed rate. Further adaptation of the feed rate can only be done manually by the operator of the machine during the cutting process.

The developed software setup allows for adaptive control of the feed rate based on the cut volume along the tool path for a specific step size. This guarantees a constant usage of the full capacity of the machine setup during the entire cutting procedure in order to reduce machining time to a minimum.

Figure 8 shows the time analysis output of the customized simulation process of the sample voussoir shown in Figures 6 and 7. The corresponding work piece (152 x 259 x 61 cm) has a weight of approximately 6.25 ton, and the inscribed voussoir has a final weight of approximately 1.54 ton. The relatively large stone volume which needs to be processed can be explained by the doubly curved top and bottom surfaces and the hexagonal shape of the voussoir that poorly fit the minimum bounding-box volume of the work piece.

The first three parts of the process, Jobs 1.1-3 in Figure 8, represent a similar cutting process as shown in Figure 6 before the stone is flipped (Fig. 6a-d). Job 1.1 represents the parallel cutting sequence with a step size of 5.08 cm (2 in) which takes approximately 25 min. The very first vertical peak of the graph in Figure 8 shows the large volume being processed while plunging into the work piece. This corresponds with the vertical tool path segment (Fig. 7a) and cutting process shown in Figure 7. In general, one straight cut is represented by a major peak following a specific amplitude pattern. The overall valley in the middle of the graph in Job 1.1 shows that less material is processed per cm of feed length due to the convex shape of the upper surface of the sample voussoir (Fig. 6b). Note that the frequency in the middle of the graph in Job 1.1 is higher meaning that more parallel cuts are process over time. Job 1.2 represents four reference cuts with a total cutting time of approximately 3 min. The straight cuts for the six contact faces follow in Job 1.3 with a total cutting time of approximately 7 min. Job 1.4 represents six additional cuts for possible advanced notching grooves with a cutting time of approximately 8 min.

The above-mentioned process results in an overall cutting time for the top side of the piece of approximately 35 min without and 43 with additional grooves along the contact faces. Taking into account the process of manually removing the leftover pieces, including disposal and cleaning (Fig. 6a,g), another 20 min needs to be added per side. The flipping and mounting of the block adds another 10 min per side. This adds up to a total machining time of 2 h 7 min without and 2 h 23 min with additional advanced notching grooves.

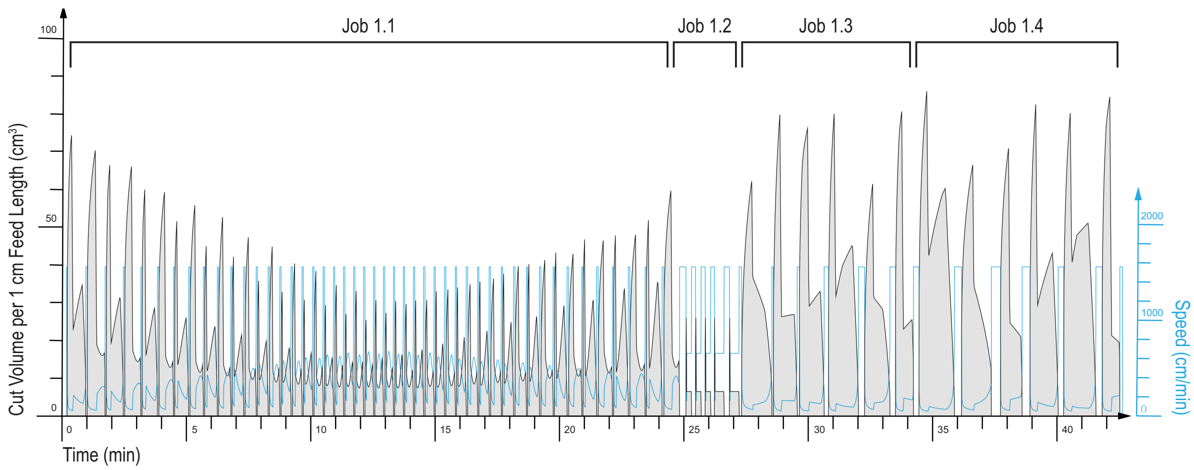

Fig. 8 Cutting time analysis of the customised simulation process, based on the sample voussoir shown in Figures 6 and 7

The relatively short machining time for a large working piece is highly dependent on the step size of the parallel cuts of the top and bottom surface. Therefore, the groove pattern gains importance, especially if the manual smoothing by grinding the surface turns out to be too labour-intensive. The orientation of the pattern should be defined globally with respect to the surrounding neighbouring voussoirs as shown in Figure 9a, in order to guarantee a more homogenous groove pattern over the vault surface. Thanks to the capability of the automated CAM setup to use information about the tessellation bond and voussoir relation, the local orientation of the pattern in relation to the global layout can be controlled easily. The flexible setup does further allow for converging groove patterns based e.g. on the local direction of steepest descent of the surface (Fig. 9b).

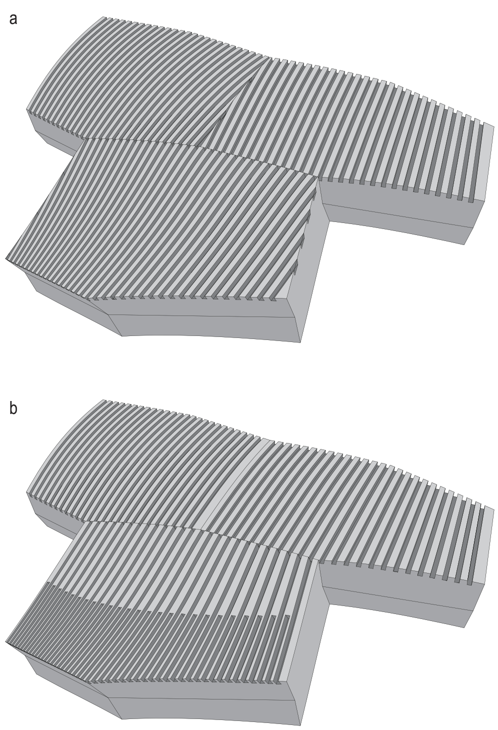

Fig. 9 The flexible CAM setup allows for detailed control over the local groove pattern in relation to the global tessellation and shape of the vaulted structure

The software results have shown that a customized CAM setup offers unique and new possibilities to enhance the fabrication process. Especially the time to digitally prepare the voussoir geometry for G-code export and the actual cutting time can be reduced to a minimum. Furthermore, new features that are not accessible in commercial CAM software could be added to the process.

5.2. Fabrication Results

Several, scaled mock-up voussoirs of the vault were processed and evaluated using the described setup. Figure 10 shows the machining process of a smaller sample voussoir (approx. 71 x 48 x 20 cm) based on the machining sequence illustrated in Figure 6.

Fig. 10 From top left to bottom right: sequential stone-cutting process of a scaled sample voussoir of the MLK Jr. Park Stone Vault

This stone-cutting process was used to calibrate and evaluate the customised CAM setup and machining strategy (Fig 11). Breaks in between cutting passes due to the documentation of the progress, adjustment and mounting of an improvised steel rack and the very small step size of the parallel cuts did not allow for a representative measure of the overall fabrication time. However, it became clear that in contrast to milling strategies, the straight cuts used for the planar contact faces significantly speed up the overall machining process. The visible offsets of contact face surfaces processed from both sides result from incorrect measurements of the tool shaft of the circular blade.

Fig. 11 Three scaled sample voussoirs of the MLK Jr. Park Stone Vault before undergoing manual surface treatment and assembly

6. CONCLUSION

This paper presented a method to enhance the CAM setup to achieve given research objectives. A machining strategy was developed to increase the feasibility of the fabrication process by minimizing cutting time while guaranteeing the required precision of the process. A prototypical, customised CAM software setup was developed and tested using simulation techniques. It features tools to efficiently generate G-code in an automated setup, precisely analyses the cutting process in order to minimise fabrication time, and offers a flexible framework to add further customised functionality. Several, scaled mock-up voussoirs of the vault were digitally and physically processed and evaluated using the described setup.

7. ACKNOWLEDGEMENTS

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The core development team of the MLK Jr Park Vault in Austin, Texas, USA consists of the following partners: client and development partner: MFI Real Estate, LLC; general contractor: Escobedo Construction, LP; stone fabrication and installation: Escobedo Construction, LP and AX5 Resources; structural design: BLOCK Research Group, ETH Zurich, Switzerland; structural engineering: Ochsendorf, DeJong & Block, LLC.

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