

Innovating structural masonry - MLK Jr. Park Stone Vault

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PROJECT OVERVIEW

This paper reports on recent developments for the demanding stone-cutting process of the MLK Jr. Park Stone Vault in Austin, TX, USA. Since 2012, the authors are deeply involved in the on-going planning process of the structural stone vault, which fosters and brings forward research on the structural design, analysis and fabrication of free-form masonry shells. The MLK Jr. Park Stone Vault will be located in the heart of the Martin Luther King (MLK) Jr. Park of the East-Austin urban development and transit-oriented district, Chestnut Plaza, where it will be used as a multi-purpose community and performance space. The discrete, unreinforced and dry-stone stone vault will cover an area of approximately 600m² with a maximum span of 30 m.

INTRODUCTION

'Good structural form' results in low compressive stresses and reduces the need for bending capacity of a structure, regardless of what material has been chosen. The research presented in this paper is based on the profound investigation on the design and materialization of such, efficient structures and driven by the fascination for the elegance of Gothic stone vaults that combine aesthetics, ornamentation, and structural logic. The research enters into the relatively new research field of digital stereotomy, which revisits and extends traditional stereotomy, the art of cutting up stone blocks or dimensioned work pieces into discrete ashlar/voussoirs, by introducing computational strategies and optimization techniques to address structural requirements and fabrication constraints. Specifically, this contribution will discuss the application of these new developments for the design and digital fabrication of the complex voussoirs for the MLK Jr. Park Stone Vault. The presented work on the fabrication strategies was conducted in close collaboration with Escobedo Construction and AX5 Resources in Austin, TX, USA.

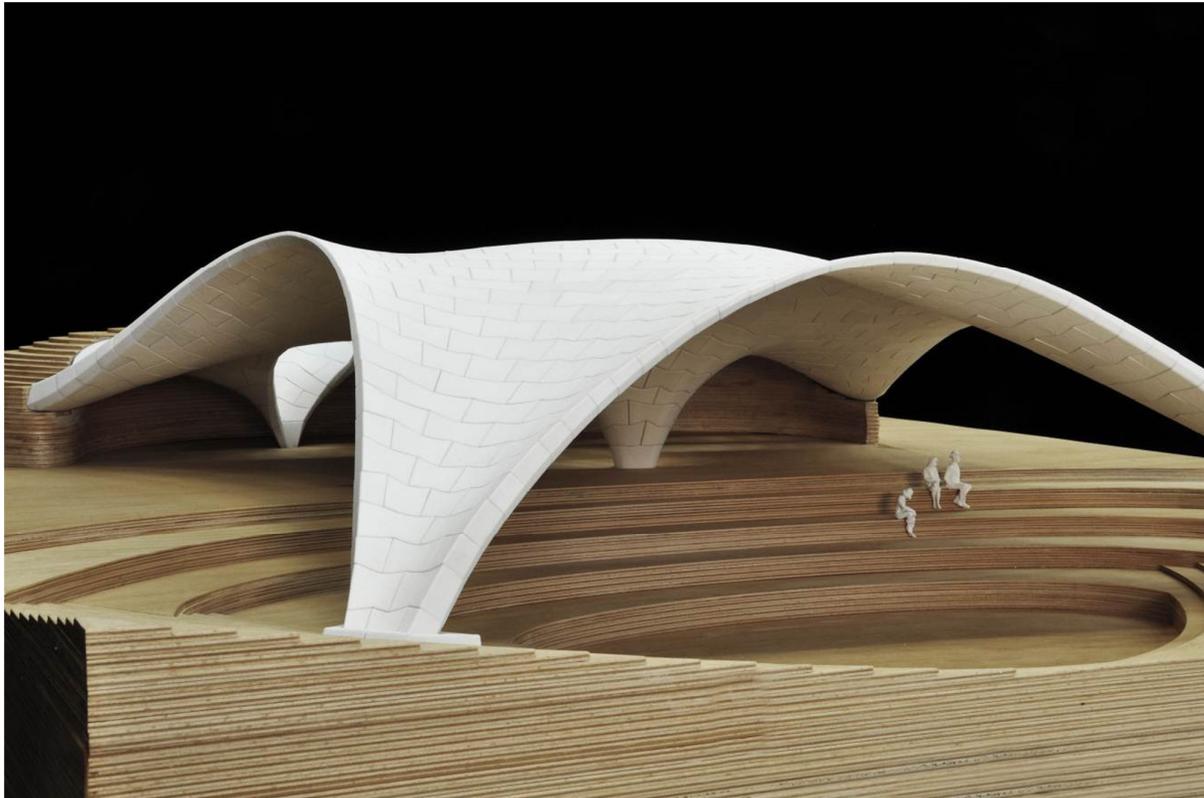


Figure 1. 3D-printed, structural (unglued) model of the MLK Jr. Park unreinforced masonry vault in Austin, TX, USA



Figure 2. 3D-printed structural model of the MLK Jr. Park free-from unreinforced masonry vault in Austin, TX, USA



Figure 3. 3D-printed structural model of the MLK Jr. Park free-from unreinforced masonry vault in Austin, TX, USA

RESEARCH GOALS

The key objective for this research is to define and develop a streamlined design and fabrication setup for the production of the hundreds of individual voussoirs of the MLK Jr. Park Stone Vault. Due to the three-dimensional shape of the separate blocks and the geometrically complex fabrication constraints, the challenge is to coordinate the design of the individual voussoirs, in accordance with the technical machine setup and machining strategy.

STRUCTURAL AND FABRICATION REQUIREMENTS

The defining structural properties for stone, or masonry in general, are its low/negligible tensile and high compressive strength. Because of this, to span space in unreinforced masonry, the use of funicular form, acting purely in compression, is mandatory to ensure structural stability. Therefore, an appropriate funicular form is determined using form-finding methods. Based on this form, a possible tessellation is generated that defines the discretization of the vault surface. Subsequently, this pattern is used to generate the voussoir geometry considering structural as well as fabrication and assembly constraints.¹ This sequential process from form finding to fabrication is illustrated in Figure 4.

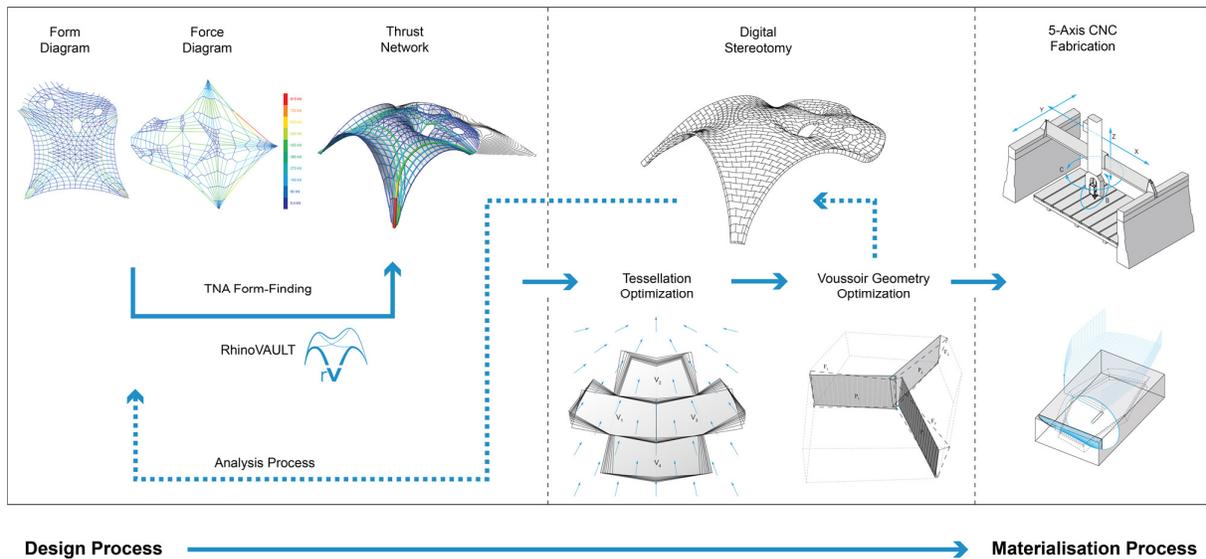


Figure 4. From Form finding to Fabrication: Design and materialization process of the MLK Jr. Park vault in Austin, TX, USA

As a structural constraint, the thickness of the vault and thus the local offset values for the voussoirs generation needs to be sufficient to provide stability under asymmetric live, i.e. non-funicular, loading and prevent buckling. Moreover, the contact faces between voussoirs should be aligned as orthogonal as possible to the force flow to prevent sliding failure between them. An additional measure to provide a three-dimensional action is the controlling of the minimal and maximal overlaps between voussoirs.

¹ Rippmann M. and Block P. Rethinking Structural Masonry: Unreinforced, Stone-cut Shells, Proceedings of the ICE – Construction Materials, 2013, in press.

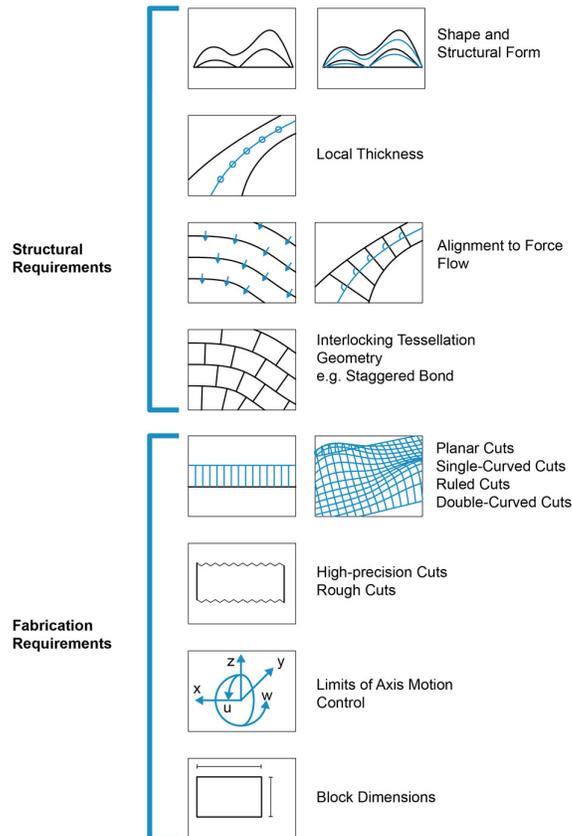


Figure 5. Constraints to be considered in the design of free-form stone vaults, grouped in structural and fabrication requirements.

FORM FINDING – STRUCTURAL DESIGN

The form finding for this case study is based on Thrust Network Analysis (TNA), which is a graphic statics-based approach to the equilibrium design and analysis of compression-only vaulted structures with complex geometry.²³ The method uses geometrically linked form and force diagrams, which can be manipulated by the designer to explicitly control or steer the funicular form finding. The form finding for the MLK Jr. Park Vault was done with RhinoVAULT, an implementation of the TNA approach for the CAD software Rhinoceros®.⁴ Form and force diagrams were defined and manipulated to find a resulting thrust network close to the initial sketch design. The explicit control over form and forces during the form finding process allows for specific, intended design features such as the “flaring-up” edge arches, an ode to the concrete shell designer, Heinz Isler (1926-2009), and the “eye openings” supported in one point, an ode to the architect Frei Otto (b. 1925), which represent a novel, formal and structural language for unreinforced masonry vaults.

In contrast with, for example, reinforced concrete shells, unreinforced, stone-cut masonry shells cannot resist bending. To resist non-funicular live load cases and avoid buckling, both the depth and the self-weight of the vault have been increased. The thickness of the MLK Jr. Park Vault ranges therefore between 250-1000 mm based on first calculations using TNA, making its self-weight clearly a very dominant loading case.

TESSELLATION

Based on the form-finding results and the structural requirements, the tessellation geometry needs to be laid out on the thrust surface such that edges are orientated as perpendicular or parallel as possible to the local force vectors, which can be deduced from the thrust network. At the same time, bounds on the edge lengths need to be imposed because of fabrication requirements. The tessellation furthermore needs to have an “interlocking bond” to allow for fully three-dimensional structural action, and to prevent sliding of individual voussoirs. To deal with these hard-to-control, interrelated criteria, an optimization scheme that simplifies the design of appropriate tessellation geometries for free-form vaults was developed and used for the tessellation design. Implemented in a digital design tool, it offers an interactive, flexible and user-driven design process, regulated and monitored automatically in real time.

² Block, P. and Ochsendorf, J., Thrust Network Analysis: A new methodology for three-dimensional equilibrium, *Journal of the International Association for Shell and Spatial Structures*, 2007, 48(3), 167–173.

³ Block, P., Thrust Network Analysis: Exploring Three-dimensional Equilibrium, PhD thesis, Massachusetts Institute of Technology, Cambridge, MA, 2009.

⁴ Rippmann M., Lachauer L. and Block P. Interactive Vault Design, *International Journal of Space Structures*, 2012, 27(4), 219–230.

VOUSSOIR GEOMETRY

In contrast to most building construction materials, natural stone demands a subtractive process for its fabrication, which inherently is less resource-efficient. Therefore, one aspect of the research is the development of efficient strategies for the machining of complex voussoirs that take into account material waste, tool degradation and cutting time.

The machine used for the fabrication results during this research is an OMAG Blade5 NC900 CNC machine at AX5 Resources, TX, USA. The 5-axis, portal router is a customised CNC machine setup and controlled via a SINUMERIK 828 CNC controller. For processing complex geometry in stone, this or similar types of 5- or 6-axes milling and circular-saw-blade machines are most popular. Usually, these machines have a portal design, capable of holding different milling heads and circular saw blades.

The fabrication requirements 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 accuracy of the contact faces. Using milling heads for cutting stone layer by layer results in very precise surfaces with total geometric freedom, but comes at the cost of relatively high amounts of waste material, low cutting rates, and fast tool degradation. The use of circular saw blades, on the other hand, minimises these, but is limited to planar cuts.

Developed optimisation strategies applied to the geometry of the voussoirs 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.

CAM PROCESS

Tests and explorations have shown that the CAM setup can be further streamlined using customised automation strategies.⁵ 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. This was realized using Rhinoceros®, 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 for a high number of individual voussoirs of the stone vault in short time. A key aspect of the software development was to guarantee the full control over relevant parameters, such as cutting volume per minute. The developed software setup allows for adaptive control of the feed rate based on the cut volume along the tool path (Fig. 6) 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.

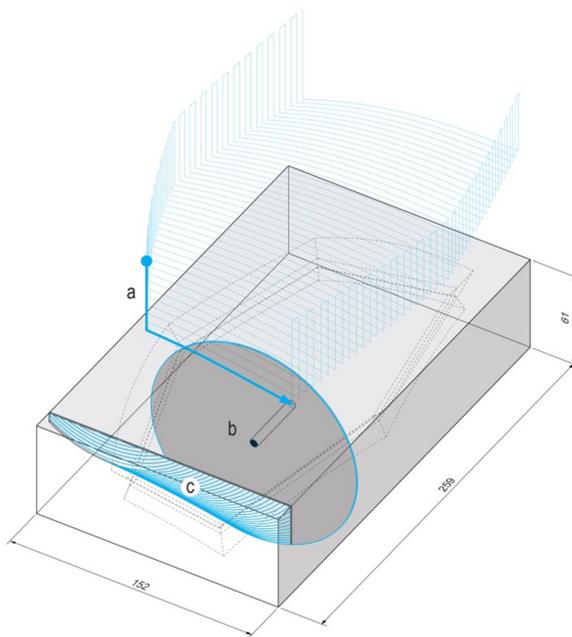


Figure 6. Tool path layout for cutting the top surface of a sample vault voussoir generated with the customised software setup.

MACHINING STRATEGY

⁵ Rippmann M., Curry J., Escobedo D. and Block P. Optimising Stone-Cutting Strategies for Freeform Masonry Vaults, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2013, Wroclaw, Poland, 2013, in press.

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. 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 re-positioning of the partly processed work piece demands high precision (approx. ± 1 mm). Specifically, the guaranteed flush alignment of the contact faces of neighbouring voussoirs within the tessellation bond demands the development of a strategy using precise re-referencing techniques. The machining sequence in Figure 7 illustrates the developed cutting strategy for a typical vault voussoir, which includes a new re-reference technique.

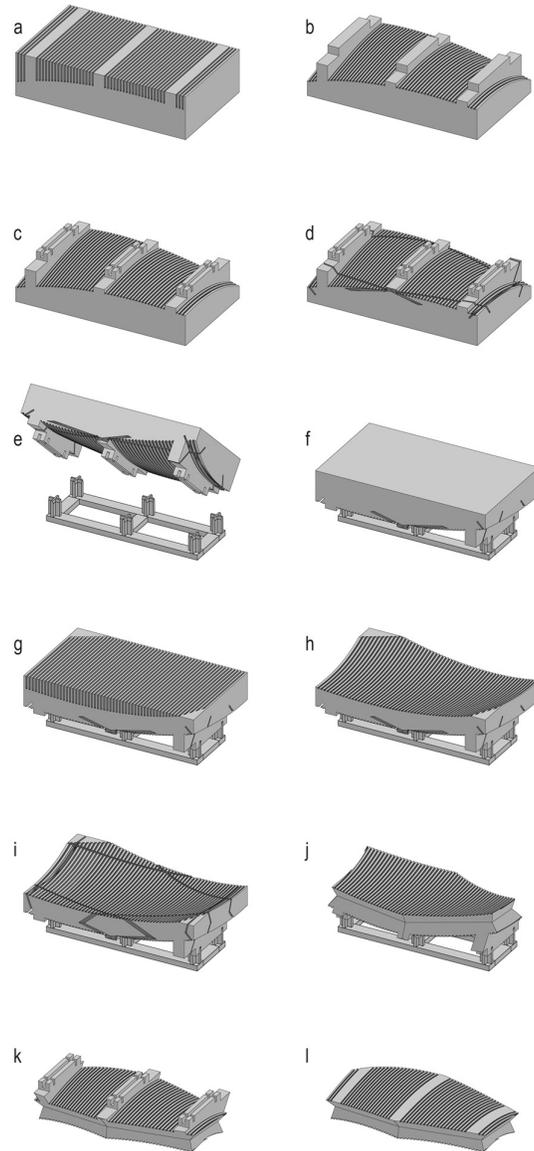


Figure 7. Machining sequence illustrating the cutting and re-referencing strategies for a typical vault voussoir

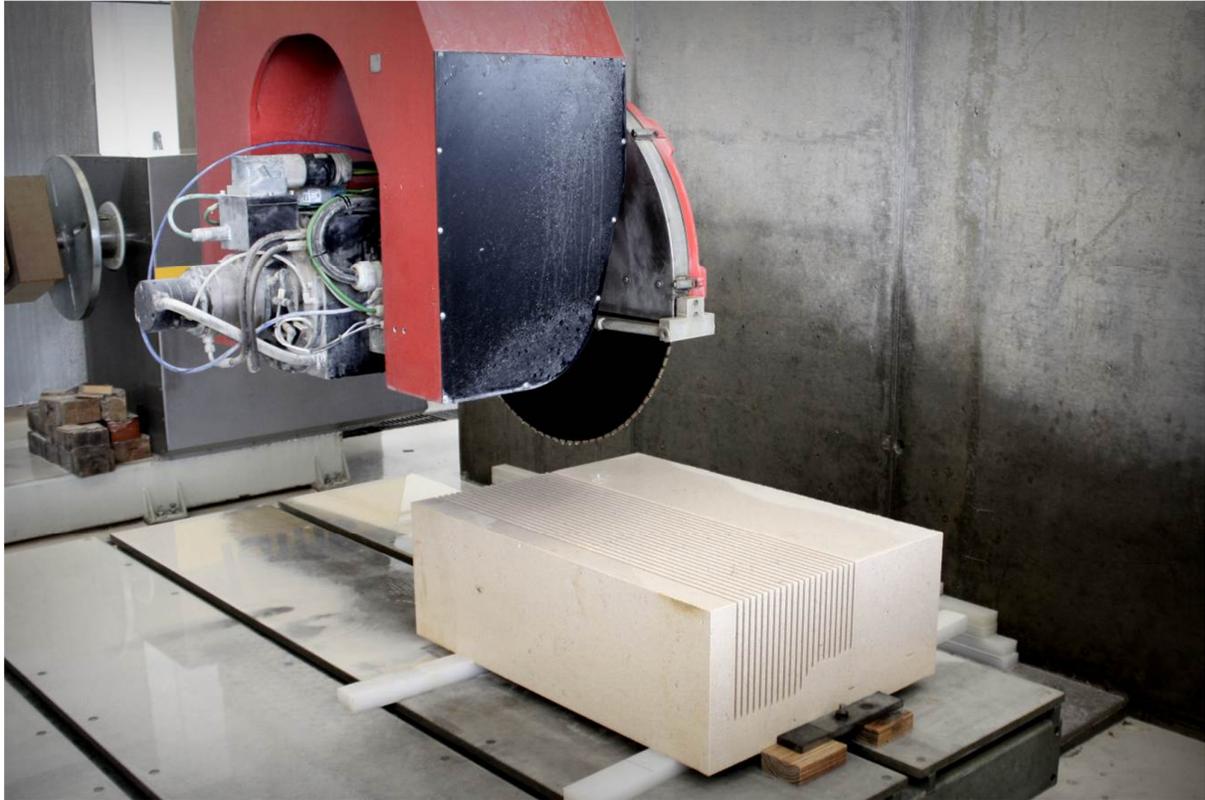


Figure 8. Cutting process on the work piece using successive parallel cuts to approximate the doubly curved top surface of a voussoir



Figure 9. The partly processed work piece is flipped using the gantry crane and positioned on the steel rack

FIRST FABRICATION RESULTS

Several, scaled mock-up voussoirs of the vault were processed and evaluated using the described setup. The stone-cutting process was used to calibrate and evaluate the customised CAM setup and machining strategy. 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.



Figure 10. Three scaled sample voussoirs of the MLK Jr. Park Stone Vault before undergoing manual surface treatment and assembly.

STRUCTURAL MODEL

Structural models allow for a first validation of and insight in structural behaviour, particularly in the case of such free-form vaults. Due to the scalability of compression-only masonry structures, they furthermore enable a reliable prediction of the stability of a real-scale stone structure for corresponding load assumptions. A first structural model of the MLK Jr. Park Vault was built to scale 1:33 using rapid prototyping techniques. All voussoirs were printed as discrete pieces using three-dimensional printing technology, and using a CNC-milled foam formwork, they were assembled without the use of adhesive. The model was used to explore the architectural quality of the vault, but also to investigate its stability and understand collapse mechanisms of the discrete voussoirs under different support displacements and concentrated live loads (Fig. 11). The model was also instrumental in examining strategies for decentring.



Figure 11. Collapse sequence of the 3D-printed structural model, consisting of separate voussoir pieces, of the MLK Jr. Park Vault (scale 1:33).



Figure 12. 3D-printed structural model of the MLK Jr. Park free-form unreinforced masonry vault in Austin, TX, USA

CONCLUSIONS

This research is driven by the ambition to breathe new life into an apparently obsolete building technique. By fully embracing new funicular form finding and structurally-informed fabrication optimisation strategies, the authors strongly believe that new forms in structural masonry can enrich the vocabulary of contemporary architecture. This paper has shown the potential of new applications of structural masonry by identifying efficient techniques for the development of discrete, free-form MLK Jr Park Vault in Austin, Texas, USA. An enhanced CAM setup and machining strategy was developed to increase the feasibility of the fabrication process. Several, scaled mock-up voussoirs of the vault were digitally and physically processed and evaluated using the described setup. Further a first structural model of the MLK Jr. Park Vault was built to scale 1:33 using rapid prototyping techniques.

ACKNOWLEDGEMENTS

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