FABRICATE
RETHINKING DESIGN AND CONSTRUCTION

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THE ARMADILLO VAULT
BALANCING COMPUTATION AND TRADITIONAL CRAFT

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This paper describes the development and fabrication of the Armadillo Vault, an unreinforced, freeform, cut-stone vault, which embodies the beauty of compression made possible through geometry. Specifically, the paper provides insights on how a highly interdisciplinary team managed to bridge the difficult gap between digital modelling and realisation by learning from historic precedent and by extending traditional craft with computation.

The vault is the centrepiece of *Beyond Bending*, a contribution to the 15th International Architecture Exhibition – La Biennale di Venezia 2016, curated by Alejandro Aravena (Fig. 2). Wrapping around the columns of the Corderie dell'Arsenale, the shell's shape comes from the same structural and constructional principles as stone cathedrals of the past, but is enhanced by computation and digital fabrication. Comprising 399 individually cut limestone voussoirs with a total weight of approximately 24 tonnes, the vault stands in pure compression, unreinforced and without mortar between the blocks. It spans more than 15m in multiple directions, covers an area of $75m^2$ and has a minimum thickness of

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only 5cm (Fig. 1). Each stone is informed by structural logic, by the need for precise fabrication and assembly, by the hard constraints of a historically protected setting and by tight limitations on time, budget and construction. On the one hand, digital tools were developed for the form-finding process of the shell's funicular geometry, the discretisation of the thrust surface, the computational modelling and optimisation of the block geometry and the CNC machining process. On the other hand, together with master stonemasons, traditional strategies of stereotomy were investigated, analysed and revisited to develop appropriate and efficient stone-cutting and processing techniques and approaches to sequencing and assembly.

The lessons learned from historical precedent, combined with traditional craft enhanced by digital computation, allowed a collaborative team of engineers, designers and skilled masons to deal with the hard constraints of the project. Although such an interdisciplinary strategy reflects the holistic approach to design and construction of master builders in Gothic times that contrasts with today's more linear building processes, the presented work is not a romantic attempt to revive the Gothic. Rather, it is a direct critique of the current practice of planning and constructing freeform architecture. It is also a demonstration of how material and fabrication constraints are not equivalent to limited design possibilities, but can be the starting point for expressive and efficient structures.

The challenges of working in a historic setting

The Corderie dell'Arsenale is a historically protected building. Therefore nothing could be attached or anchored to the walls, columns or floor. Additionally, the average stress on the floor could not exceed $600kg/m^2$, which corresponds to that caused by a tightly packed crowd of people. This also meant that no heavy equipment, such as a mobile crane, could be used for the assembly. Thus alternative methods for the manual setting of stones had to be developed. Furthermore, only five months were available for the entire project. This includes time needed for the design, engineering, fabrication and construction of the vault. The challenge was effectively to convert a 'perfect world' digital design into a 'real world' fabrication and construction process in an extremely short period of time for a constructional/ material system without obvious mechanisms to compensate for tolerances.

Digital process

For this project, a smooth digital pipeline/workflow was developed to realise a structurally optimised and fabrication-driven generation of geometry.

Structural design and analysis

The vault's funicular geometry, which allows it to stand like an intricate, three-dimensional puzzle in pure compression, results from a form-finding and optimisation process based on thrust network analysis (Block & Ochsendorf, 2007, Van Mele et al., 2014). These novel computational methods offer a more controlled, force-driven exploration of (inverted) hanging models.

The dominant self-weight of the vault was taken as a design load to define the middle surface of the structure, which was then offset according to assigned local thicknesses based on experience and weight constraints (Van Mele et al., 2016). The resulting intrados and extrados define a local shell thickness ranging from 5cm at the midspan and only 8cm along the line supports to 12cm at the internal touch-down and point springing (Fig. 3).

Based on the designed force flow, the stone envelope was discretised into courses and the courses into voussoirs. Staggering of the voussoirs, and alignment of the courses to the force flow and the boundary, guaranteed proper interlocking of all stones in the surface of the discrete shell (Fig. 4). To speed up the fabrication process, the voussoirs were made as large as possible with an approximate range of 45 to 135kg, so that they could still be handled by hand or with a lightweight jib crane. The stability of the unreinforced, dry-set assembly under various load conditions, including concentrated loads, settlements of the supports and earthquake loads, was confirmed using discrete element analysis (Van Mele et al., 2016).

Architectural geometry and fabrication

Due to the limited timeframe and large number of voussoirs, the main goal for the fabrication process was to reduce the average cutting time for each stone. Additionally, since there is no mortar between the voussoirs, which could have compensated for tolerances, the interfaces between stones had to be flush and therefore precisely cut and set.

To optimise the fabrication process, the voussoirs were designed to have a convex cutting geometry along the interfaces, such that they could be cut efficiently with a circular saw (Rippmann et al., 2016). However, the vault has several areas with negative Gaussian curvature. Since it is geometrically impossible to discretise such a surface with a convex, planar mesh (Li, Liu & Wang, 2015), the faces of the extrados were allowed to disconnect and create a stepped, scale-like exterior. This visually emphasised the discrete nature of the shell and allowed the flat extrados faces of the voussoirs to be used as a base for the machining process. As a result, the cubic blanks no longer needed to be flipped and re-referenced, reducing fabrication time of the voussoirs significantly. The curved intrados faces were formed by side-by-side

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1. The Armadillo Vault spans more than 15m with a maximum height of 4.3m and a minimum thickness of only 5cm. A system of tension ties balances the thrusts of the compression shell. Image: Iwan Baan.

2. The Armadillo Vault in the Corderie dell'Arsenale at the 15th International Architecture Exhibition – La Biennale di Venezia, 2016. Image: Anna Maragkoudaki/ Block Research Group, ETH Zurich.

3. The local shell thickness ranges from just 5cm at the midspan to 12cm at the internal touch-down and point springing. Image: Anna Maragkoudaki/ Block Research Group, ETH Zurich.

4. The overall tessellation design is defined by stone courses aligned perpendicular to the local force flow. Image: Aman Johnson.

cuts with a circular blade, spaced such that thin stone fins remained. Rather than milling these away, the fins were hammered off manually to create a rough but precisely curved surface. The side surfaces perpendicular to the force flow were processed with custom profiling tools that create ruled surfaces with male/female registration grooves. These grooves are primarily used as reference geometry to assist assembly, but also prevent local sliding failure. The other side surfaces of each voussoir were created with simple planar cuts.

From digital to realisation

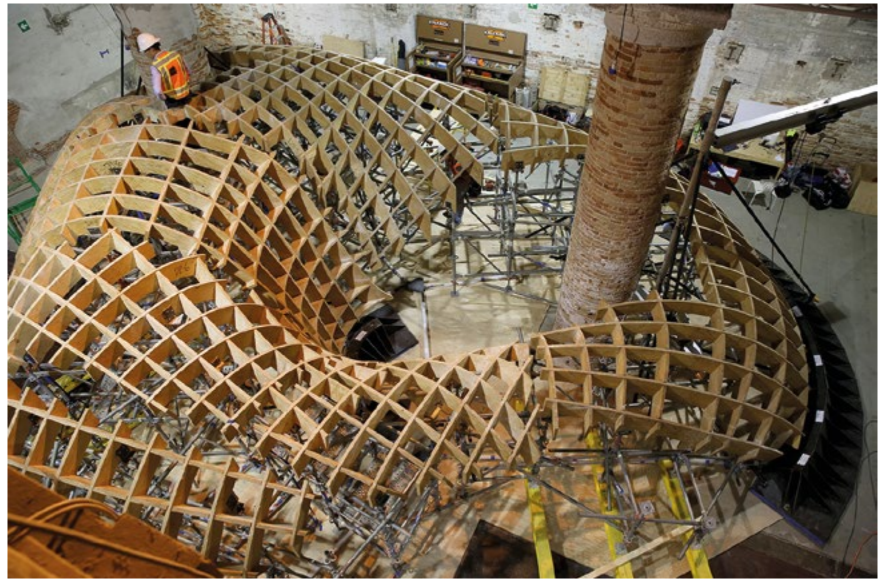
The vault was test-assembled offsite to allow a team of expert stonemasons to become familiar with the process. During the test assembly (and also during onsite assembly), each voussoir was fully supported by a falsework consisting of a standard scaffolding system with a custom-made wooden grid on top (Fig. 5). The voussoirs were placed manually, starting from the courses at the supports and converging towards the 'keystone' courses at the top. To gradually decentre the vault as evenly as possible, a specific sequence for lowering the falsework was determined, cycling through the independent scaffolding towers in several rounds.

Using imprecise formwork

In traditional cut-stone or stereotomic stone vaulting, voussoirs are never placed directly on falsework. Instead they are positioned using shims. This insight was used as a pragmatic formwork strategy that provided a way to deal with the rough interior surfaces of the stones. The wooden falsework was offset inward/downward by 3cm. As a result, large wooden shims could be placed in between the rough, knocked-off fins to support the stones on the falsework and precisely control their position. Additionally, this meant that precise positioning of the falsework sections was less critical. This resulted in significant time-saving and reduced logistical challenges. As an added bonus, the shims served as visual guides during decentring. Once they started falling on the ground, the shell was standing by itself.

Not building the designed geometry

Due to unavoidable machining tolerances, each of the voussoirs could only be within +/-0.4mm of the designed digital geometry. Since the vault was designed to have a high degree of structural redundancy and indeterminacy by introducing locally high degrees of double curvature, these small imprecisions had little or no effect on the structural integrity and behaviour of the overall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5. The falsework consists of a plywood waffle structure on top of standard scaffolding towers. Image: Anna Maragkoudaki/ Block Research Group, ETH Zurich.

6. The stone courses were built up starting from the supports. Voussoirs of the edge arches were positioned before closing the subsequent course to better control the global positioning of the stones. Image: Anna Maragkoudaki/ Block Research Group, ETH Zurich.


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7. The different articulation of the intrados and extrados of the stone shell results from a combination of fabrication constraints, machining efficiency and aesthetic considerations. Image: Iwan Baan.

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8. The finished cut-stone vault wraps around an existing column in the Corderie dell'Arsenale. Image: Iwan Baan.

9. The pattern on the intrados is carefully controlled to globally align with the flow of forces within the stone structure. Image: Anna Maragkoudaki/ Block Research Group, ETH Zurich.

10. The intrados pattern makes the structure's geometry more legible. Image: Philippe Block/Block Research Group, ETH Zurich.

structure. However, over 14 courses of stones, these tolerances can quickly add up to large geometric discrepancies in the 'keystone' rows. Therefore the voussoirs in these rows were cut last, after construction had already begun, based on measurements of the partially assembled structure. Before decentring the test assembly, the 'as-built' geometry of the structure was recorded and the position of each stone relative to its neighbours was marked on the interfaces.

Since slight deviations of a fraction of a degree in placement angle at the base (or in fact anywhere along any row) cause significant deviations higher up, several strategies had to be developed. The masons would build a few rows, finish some of the edge arches and check that everything closed. If not, they would take down the rows, adjust, reposition and realign, repeating the entire process as needed (Fig. 6).

For structural reasons, it was much more important to have contacts that were as tight as possible between stones so that, after decentring, no uncontrollable and unpredictable settling of the assembly would occur. Using the above-mentioned shimming, the masons 'jiggled' every stone until all interfaces were tight. Where necessary, the interfaces were sanded off to improve the fit. The level of precision reached through manually trimming a stone depends on its initial geometry. Flat surfaces can easily be processed with simple templates and tools. Therefore the geometry of all interfaces was constrained to planar and ruled surfaces depending on their local alignment to the courses being perpendicular or parallel respectively.

A successful marriage of precision engineering and craft experience

The Armadillo Vault represents the close collaboration of engineers, designers and skilled stonemasons and builders. It is the culmination of over 10 years of joint research in stone construction, demonstrating that, with advanced, non-standard engineering approaches and novel equilibrium design methods, expressive geometries can be safely developed and – through combining optimised digital fabrication processes and experienced craft – successfully constructed. Proportionally only half as thick as an eggshell and standing without steel reinforcement, the expressively flowing stone surface challenges the conception that complex geometry need go hand-in-hand with inefficient use of material (Figs. 7–10). While the vault's architectural geometry was optimised in order to achieve all structural and fabrication constraints, and although a smooth digital pipeline with advanced data structures was developed to eliminate any possibility of human error in the handling and logistics, in the end it was the experienced human hand that locally controlled precision.

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