Structural design, fabrication and construction of the Armadillo vault

50 StructuralAwards2017

Commendation: Award for Small Projects and Award for Structural Artistry

Synopsis

The Armadillo vault, exhibited at the 2016 Venice Architecture Biennale and commended at the 2017 Structural Awards, is a doubly curved, unreinforced, cut-stone, compression-only vault, constructed from 399 limestone blocks. The thickness of the stone varies from 8–12cm at the supports to 5cm at the peak. With a height of 4.4m and spans of over 15m, the structure has a thickness-to-span ratio half that of an eggshell.

This paper describes the form-finding process and detailed structural analysis. Steel supports were designed to take the reaction thrusts of the vault and transfer them safely to both the ground and the internal steel tie system. The stone-cutting process for the limestone is also outlined, describing the rough-finished inner surface, which was patterned to follow lines of internal force flow, and the smooth flat outer surface. Finally, the process of erecting the formwork and falsework on site is also set out, including the process of decentring and the use of custom keystones.

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Figure 1
Armadillo vault – doubly curved, unreinforced, compression-only vault, constructed from 399 thin limestone blocks with span of over 15m

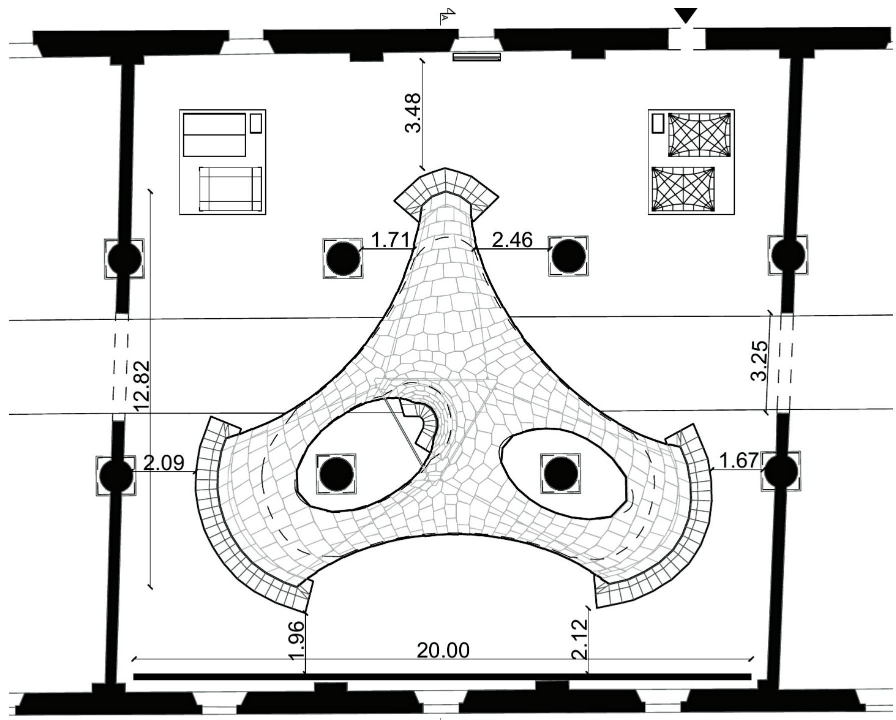


Figure 2
Plan view of Armadillo vault in Corderie dell'Arsenale building

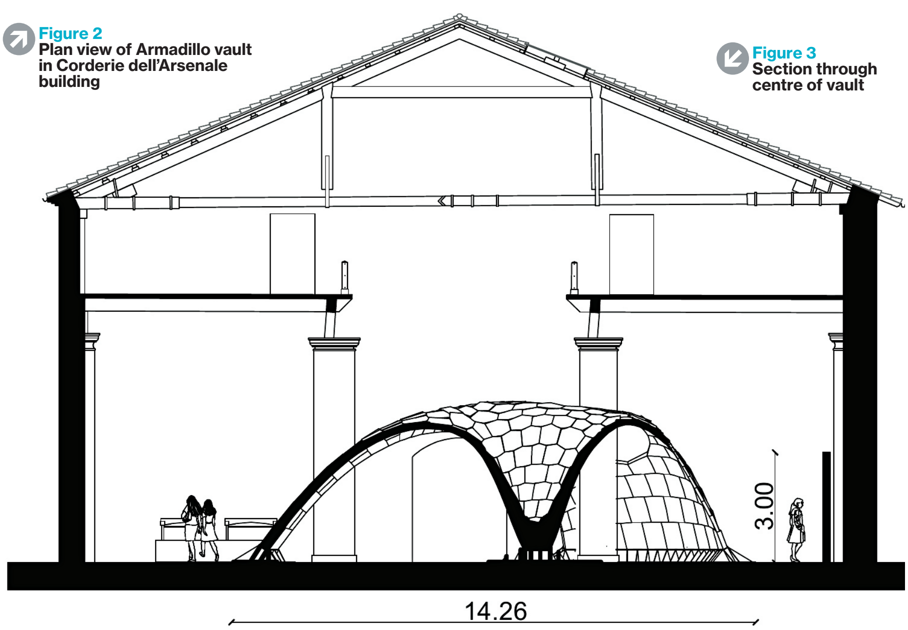


Figure 3
Section through centre of vault

Introduction

The Armadillo vault (Figure 1) is a doubly curved, cut-stone, compression-only vault, constructed from 399 limestone blocks and exhibited at the 2016 International Architecture Exhibition – La Biennale di Venezia in Italy. The project was commended in the Small Projects and Structural Artistry categories of the 2017 Structural Awards.

The thickness of the stone blocks, also called voussoirs, varies from 8–12cm at the supports to only 5cm at the vault's peak. Given its height of 4.4m and span of over 15m, the structure has a thickness-to-span ratio half that of an eggshell. The vault is roughly triangular in plan by virtue of its three perimeter supports, and possesses an additional fourth funnel touchdown support at the structure's centre (Figures 2 and 3).

The design, fabrication, transportation and erection of the vault were all influenced by various constraints, including a tight deadline of only five months (excluding transport) from inception to installation. Other challenges included the transport logistics from the quarrying and stone-cutting location in Texas, USA, to the vault's exhibition location in Venice, Italy, and various site constraints relating to the heritage of the installation building.

Modern methods of computational form finding, structural analysis and digital fabrication were all interwoven to create a compression-only masonry structure inspired by traditional masonry craftsmanship and analysis methods. The vault was designed by the Block Research Group at ETH Zurich and Ochsendorf DeJong & Block (ODB Engineering), with fabrication and erection handled by the Escobedo Group, Texas. It stands as an example of using computational methods and digital fabrication to design an elegant masonry form, from a material traditionally used for its compressive strength, rather than modern engineering materials and members that utilise flexural strength.

The vault was part of the 'Beyond Bending' exhibition at the 2016 Venice Architectural Biennale, informing visitors of the advantages of structures working in compression. The entire structure at the exhibition was kept exposed to visitors, from the differing textures of the inside and outside surfaces of the stone, to the steel support system holding the vault in place. Doing so allowed visitors to 'see' and 'touch' the static equilibrium of over 23t of stone.

Figure 4
Doubly curved geometry of vault was found through process of form finding for compression-only structure

Compression-only vaults

Masonry structures that act primarily through compression have a rich history with the master builders of domes, cathedrals, vaults and bridges. Before the wide adoption of concrete and steel as standard building materials, builders used the material of the time, which was stone, and managed to construct masterpieces that have stood for centuries. They are still celebrated today, thanks to the strong compressive strength of masonry and an attention to structural form[1,2]. Not only do these structures still inspire wonder through their elegance, they also serve as examples of how one can use material efficiently by making use of efficient geometry. In the past, the process of determining what was a good form had developed over many centuries of construction, with the fittest and most refined geometries persevering.

More recently, physical and experimental methods of determining geometries that stand in pure compression were studied and applied by key figures such as Antoni Gaudí and Heinz Isler in the 19th and 20th centuries, respectively. Today, advances in computational form finding, structural analysis tools and digital fabrication processes have provided more confidence in understanding and analysing compression-only structures, allowing us to realise expressive geometries without the need to use physical modelling, which in turn has led to the creation of structures that minimise the amount of material used.

> **"ESTABLISHING A STRUCTURAL GEOMETRY THAT IS COMPRESSION-ONLY INVOLVES A PROCESS OF FORM FINDING"**

Establishing a structural geometry that is compression-only involves a process of form finding. Often in modern engineering, a geometry is expressed explicitly and sometimes fixed quite early in the design process, with the stress analysis and the determination of the required sizes of the members following. With form finding, one starts more openly with definitions of the structure's stress state, by restricting the geometry to be, for example, compression-only for the given loading state and by imposing various constraints such as the boundary conditions.

As the Armadillo vault is an unreinforced structure, i.e. without any tension elements such as internal steel reinforcement bars, it was important for the structure to be in a compression-only stress state under its main self-weight load, but also other load cases. The resulting doubly curved shape is a geometrically stiff structure, which allows a reduction of the overall weight (Figure 4). This was an important design criterion, as it was imperative not to overload the heritage floor of the exhibition space.

Figure 5
Structure wrapping around two existing columns in exhibition space

Venice Biennale site

From the inception of the Armadillo vault to its installation on site, there was a total of only six months. This time was used for the design of the vault, the design and fabrication of the supports, cutting the stones, the design, fabrication and testing of the formwork, transporting all of the elements across the Atlantic Ocean, and then finally installing the structure for the

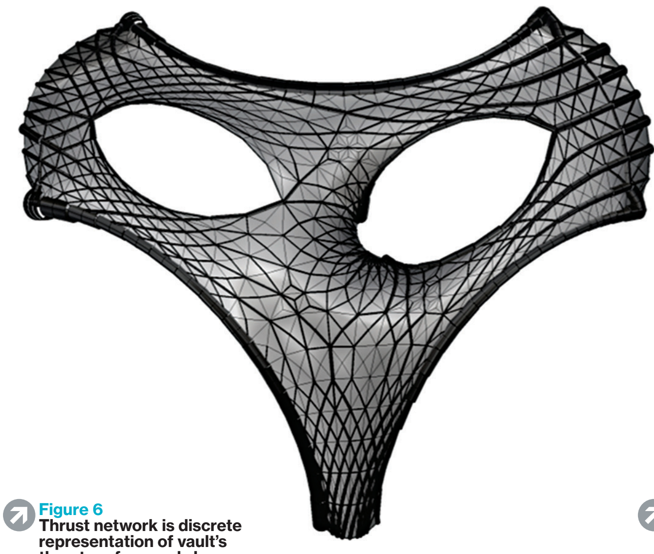


Figure 6
Thrust network is discrete representation of vault's thrust surface and shows flow of compressive forces

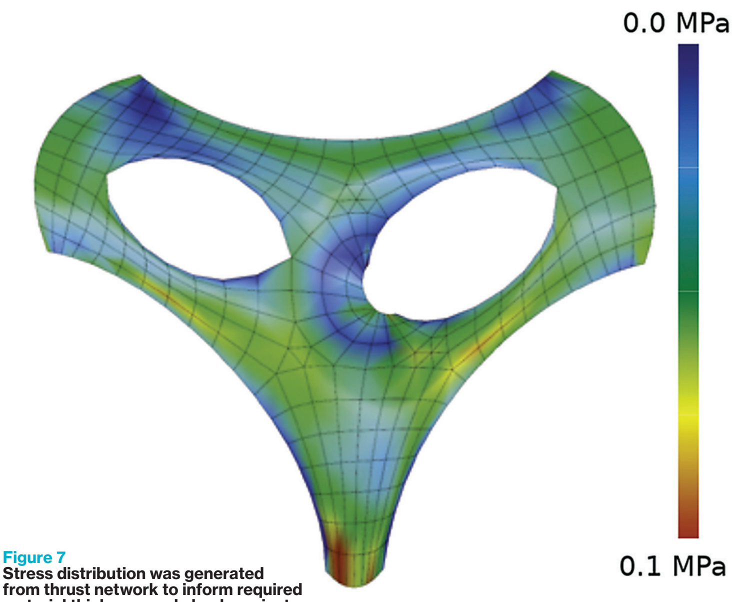


Figure 7
Stress distribution was generated from thrust network to inform required material thickness and check against allowable design stresses

exhibition. As a consequence of the short timeline, time became a governing constraint that influenced logistics, stone cutting and the vault's design and analysis.

The Armadillo vault was housed in the Corderie dell'Arsenale building, in the centre of the room, as part of the 'Beyond Bending' exhibition, displayed by the Block Research Group, ODB Engineering and the Escobedo Group. The Corderie dell'Arsenale is located in the southeast of Venice and dates back to the 13th century, having been developed for military use, and has since been used as an exhibition area for La Biennale di Venezia since 1980. The Corderie building on the southern side of the Arsenale was built in 1303 and then rebuilt in the 16th century. The rich history of the building greatly influenced both the design and installation, requiring particular care in order to delicately and precisely install 23t of stones and the supporting structure, while simultaneously wrapping it around two existing columns (Figure 5).

The resulting structure spans over 15m, provides cover for an area of 75m^2 and has a surface area of 106.5m^2. Large contact areas underneath the steel supports, which are stiffened with additional vertical plates, were used to spread the load from the vault onto the existing floor. The design contact pressures underneath the supports were limited to 65kPa, to make sure that the maximum contact pressures imparted onto the floor would not differ greatly from peak footfall pressures caused by the walking of a typical visitor.

As there could be no fastening or anchoring into the floor, the structure's outward reaction forces had to be self-equilibrated with a tie system. The ties were left exposed, save for some steel covers to protect them from visitors standing directly on them, but still allowing visitors to see and appreciate that to mobilise the vaulting action, the horizontal thrusts needed to be tied back. Similarly, to preserve the floor's condition, heavy lifting equipment and mobile cranes were not allowed during erection, influencing the number and size of the stone blocks and steel elements, as well as the erection method[3].

Vault design

This section presents the form-finding process behind the geometry of the vault, looks at the voussoirs, and provides a summary of the equilibrium analysis through discrete-element analysis.

Form finding

The geometry of the Armadillo vault is the result of a form-finding process based on computational extensions to graphic statics through thrust network analysis. Thrust network analysis is a method that has been developed at Massachusetts Institute of Technology (MIT) and the Block Research Group[4,5] and through the freely available plugin RhinoVAULT for CAD software Rhinoceros. The RhinoVAULT implementation can be used for the preliminary design of compression-only vaults[6,7], as was the case for the Armadillo. This allowed the controlled exploration of a wide variety of inverted funicular (compression-only) solutions through explicit manipulation of both the layout and discretisation of the form diagram, and the horizontal equilibrium of thrusts[8].

The design process began with hand sketching of ideas to generate different layout options, and was followed by direct form finding (RhinoVAULT sketching) to explore compression-only solutions. The selected solutions were further refined to precisely satisfy architectural constraints, such as head clearance, as well as structural requirements, such as the need for local synclastic double curvature and a balanced distribution of thrusts along the outside supports.

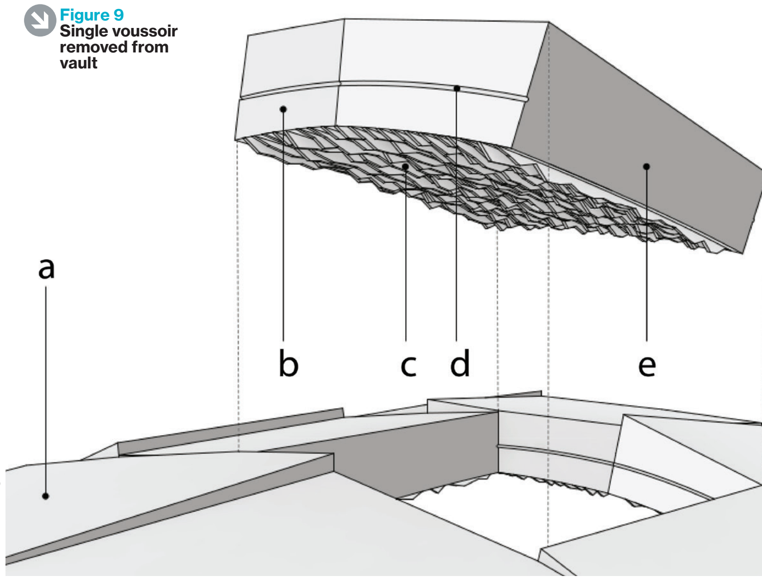
The form finding started with the creation of a three-dimensional (3D) thrust surface, which represents the centroidal surface of the vault. This thrust surface was constructed so that it was in equilibrium with the applied loading, which was predominantly based on the self-weight of the structure. A closest fit was generated through a best-fit algorithm[9] to find the internal forces of the thrust network for which the 3D network was as close as possible to the target. The thrust surface was then offset in both directions to form the outer surface, called the extrados, and the inner surface, called the intrados. It was prescribed such that the thrust surface and the designation of the stone thickness allowed the surface to remain within the middle third of the structural thickness, to cater for other non-self-weight dominated load cases.

The thrust network shown in Figure 6 shows how the compressive forces gather along the open boundary of the structure and also accumulate towards the supports, where the vertical loads have gathered, and now impart reactions to the supporting structure. The reaction force vectors were fed to the supports design as detailed later. Further details on the form-finding method can be found in Van Mele *et al.*[10].

Due to the interactive digital process, it was straightforward to redistribute the

Figure 8 Eccentric load test on two stacked dry-stone cubes to investigate potential for local spalling or fracture of stone

Figure 9 Single voussoir removed from vault



ADAPTED FROM RIPPMANN ET AL.[11]

Key:
a) Flat extrados surface
b) Double-ruled (two distinct lines exist on surface for each point) loadbearing surface
c) Rough intrados surface
d) Registration notch
e) Planar non-loadbearing surface

internal forces to avoid force concentrations occurring within the vault and to redistribute the reactions at the supports to limit areas of high contact pressures at the base.

After calculating the internal compression forces, these forces informed the stresses and thickness of the voussoirs, to then be checked with the material limits. Despite the already thin sizes, the calculated stresses plotted in Figure 7 highlight the structural efficiency, as they were still below 0.1MPa, which is considerably below the design strength of 10MPa, as described in the next section.

Voussoirs

Each stone, or voussoir, was cut from Cedar Hill cream limestone, quarried in Texas, with a density of 2320kg/m³. From a structural standpoint, the primary concern

Figure 10 Cut-line pattern on intrados was created to follow internal force flow from thrust network analysis

for material failure was through local stress concentrations building up on the edge of the stone due to potential hinging behaviour. This could have resulted in the spalling or cracking of the stone, and so to guarantee the safety of the vault, experimental tests were carried out on a series of 100mm × 100mm × 100mm cubes. These cubes were tested in compression with the applied load centred 6mm and 12mm from the edge (Figure 8). The results of these tests gave compressive strengths within the range of 20–44MPa, depending on the location of the eccentric load and the assumed stress distribution, which was either triangular or rectangular in shape. Based on these test results, the safe design limit for compressive stress was determined to be 10MPa.

On the outer surface of the vault, the stones are planar, with not all side face areas of the voussoirs (Figure 9) in full contact with their neighbours, creating relative steps of 2–5cm between voussoirs. On the inner surface, there are cut patterns representing the internal force flow (Figure 10), i.e. the internal thrust lines deriving from the thrust network described previously. The force flow also informed the tessellation pattern, as the main load-transferring voussoir interfaces are ideally encouraged to be perpendicular to the axial compression force directions, so that normal contact forces are dominant and the reliance on friction is minimised. Further information on the tessellation procedure and patterning can be found in Rippmann *et al.*[11].

Discrete-element analysis

For the equilibrium analysis, the discrete-element analysis software 3DEC[12] was used, with all external surfaces of the voussoirs triangulated, and their interiors discretised into tetrahedrons. Four load cases with various sub-load cases were analysed. These are summarised as: case 0) self-weight load due to gravity only (Figure 11a); case 1) additional line loads as well as gravity load applied to a selection of strips and in 200kg increments (Fig. 11b); case 2) gravitational and concentrated loads applied to single stones and sets of three blocks in 20kg and 100kg increments, respectively (Fig. 11c); case 3) gravitational load and constant horizontal acceleration loads applied in increments of 0.025 g in different directions (Fig. 11d).

According to the Italian seismic code, the peak ground acceleration required for the design was 0.0527 g, based on a probability of exceedance of 22% in 50 years. This value increased to 0.0689 g if the vault was considered as a permanent structure, with a 10% probability of exceedance in 50 years. The maximum possible spectral response was conservatively estimated by taking the peak value of the design spectra, which is approx. 0.15 g and occurs at a period of 0.2 seconds. For the analysis, the horizontal acceleration was increased until collapse, where the vault achieved at least 0.325 g depending on the direction of loading. This is significantly above both the peak ground acceleration and the peak spectral acceleration values.

Design of supports

The vault comes into contact with the ground via four steel supports: two long supports at the sides and two short supports at the perimeter and the central touchdown. The vertical components of the vault's thrusts are taken to the ground by the support structure, while the horizontal components are taken internally with the tie system.

Steel supports

The plated steel supports were designed to transmit the vertical reaction forces to the ground over a large area, so as to minimise contact pressures on the heritage floor. They were designed with a thick baseplate of 20mm and stiffened with many vertical stiffener plates along their lengths. The height of the supports varied between 330–430mm (depending on the inclination of the supporting plate), with widths between 1060–1200mm and lengths between 3.0–3.2m for the short supports and 6.7m for the long supports. Except for the baseplate, the thickness of the steel plates was 10mm, and proportioned such that distances between stiffeners led to Eurocode 3 class 1 elements[13].

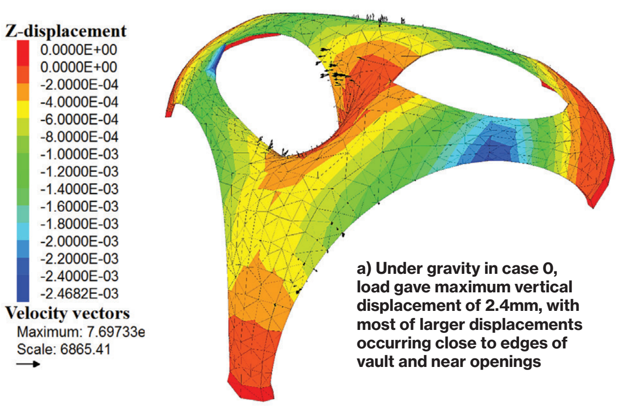
A design peak stress of 65kPa was set as the upper limit for contact stresses, taken at the level below the grout under the baseplates. A variety of parameters in the analysis were varied to meet this limit, such as the weight of the supports, number and shape of the vertical stiffeners, and the geometry of the supports.

Due to the length of the supports and the implications on manual handling and logistics, they were partitioned into discrete parts during fabrication (Figure 12). The individual boxed parts were then spliced together with steel tabs and M12 bolts, with eight bolts per splice line for sufficient shear capacity to the baseplate.

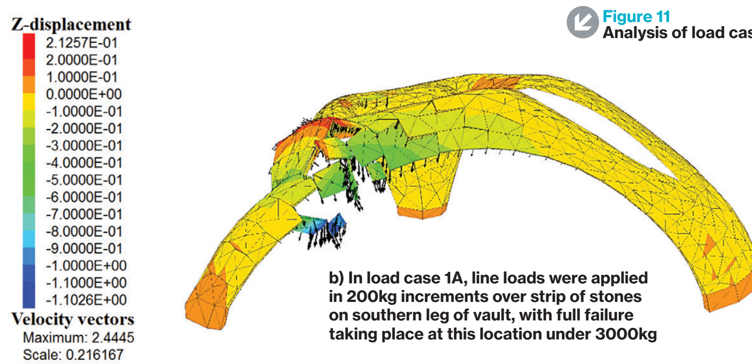
The finite-element software Abaqus[14] was used for the stress analysis, with the plated elements discretised into triangular thin-plate shell elements and connected to a ground of solid block elements. The nodes of the baseplate were connected to the ground such that no sliding could occur, due to the knowledge that the horizontal tie system would restrain lateral displacements. The loading was applied normally to the top plates via distributed pressure loading based on the distribution of reaction forces. The vertical reactions of the vaults at each support varied from 36–74kN.

Strength did not govern in the design of the supports, as plate element stresses under factored loading were below 50MPa for all supports. This is shown by the maximum Von Mises stresses plotted on the support in Figure 13. Also plotted in

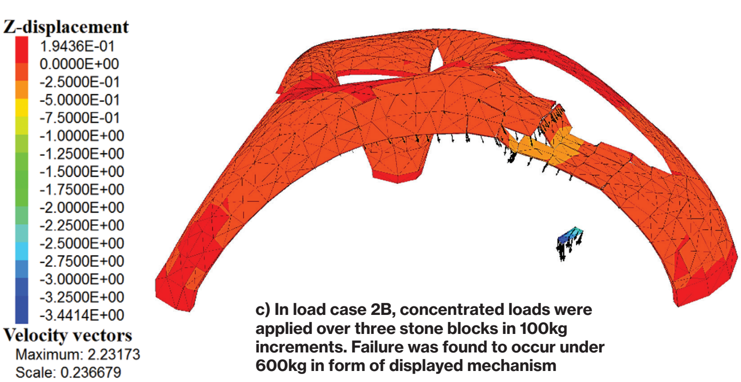
Figure 11
Analysis of load cases



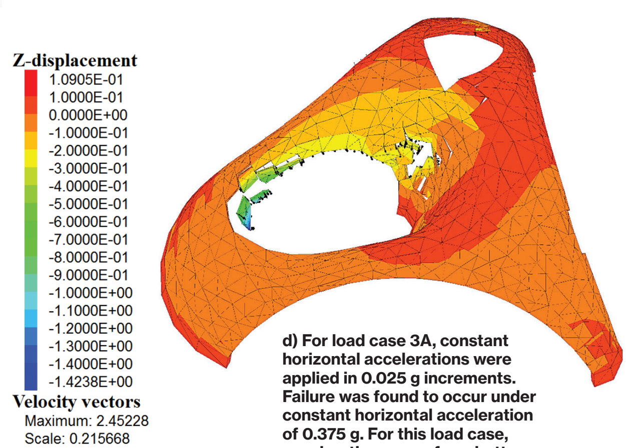
a) Under gravity in case 0, load gave maximum vertical displacement of 2.4mm, with most of larger displacements occurring close to edges of vault and near openings



b) In load case 1A, line loads were applied in 200kg increments over strip of stones on southern leg of vault, with full failure taking place at this location under 3000kg



c) In load case 2B, concentrated loads were applied over three stone blocks in 100kg increments. Failure was found to occur under 600kg in form of displayed mechanism



d) For load case 3A, constant horizontal accelerations were applied in 0.025 g increments. Failure was found to occur under constant horizontal acceleration of 0.375 g. For this load case, accelerations were from bottom-left to top-right direction

Fig. 13 are the normal contact stresses on the ground, in units of kPa, up to the target limiting stress of 60kPa. In this structural model, these are the normal contact stresses between the solid ground elements and the base of the shell steel elements. Without accurate information on the ground stiffness, a sensitivity study was performed by varying the ground's assumed Young's modulus value and taking conservative values of contact stress.

Horizontal system

A steel tie system connected the three perimeter supports and transferred the horizontal thrusts produced by the vault into internal tie forces. A tensile stress state was possible, as the vault always pushes outwards, stretching the ties connected to the supports' baseplates, while simultaneously creating extensions in the central triangle. The central support was not connected to the tie system due to the near vertical orientation of the middle touchdown, giving little net horizontal force. As the main ties that emanated from the triangle created bays that were not braced, the torsional stiffness of the vault was taken to be sufficient to resist any sway movement.

As the baseplates for the supports were fabricated from 20mm thick steel, they were considered as flexurally stiff deep beams in the plane of the ties. The resultant horizontal reactions from the vault were between 25–32kN, leading to tie forces between 13–17kN. Stainless steel ties of 19mm diameter were used for a working load of 17kN, giving a yield load of 82kN. The tie lengths were between 5.0–6.3m and the ties were covered with a steel ramp to avoid loading from visitors stepping on them, to reduce the tripping hazard and to provide wheelchair access. The central triangle was constructed from 50mm × 50mm × 6.4mm square hollow sections (SHSs), with 12.7mm thick plates at the corners acting as a node for the incoming ties (Figures 14 and 15).

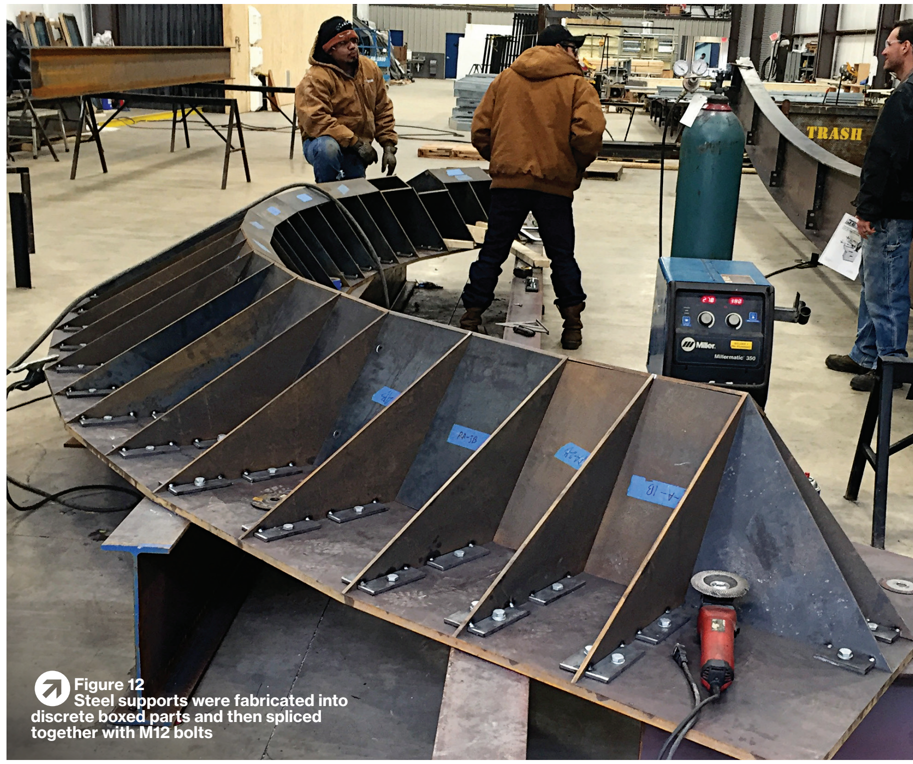


Figure 12
Steel supports were fabricated into discrete boxed parts and then spliced together with M12 bolts

Fabrication and erection

Due to the complexity and wide variety of voussoir geometries, computational methods were required to drive the optimisation of the voussoir geometry and the cutting of the hundreds of stones in the fabrication process. In this section, the stone computer-numerical controlled (CNC) cutting procedure used is described, followed by the erection steps for the installation at the exhibition.

Stone cutting

The limestone blocks were first taken from the quarry and cut into blanks with a two-axis Pellegrini wire-saw machine and then cut transversally and longitudinally using a three-axis Park Industries Predator blade saw. The cut volumes were based on bounding boxes generated from the 3D models of the voussoirs grouped to optimise the blank cutting. These volumes were all cut within five weeks to the final voussoir geometries with masses from 45kg at the top of the vault to 135kg at the supports. Due to the large number of voussoirs that were required and the tight time constraints, it was important to be efficient with the time spent on the stone-cutting machinery.

For the final machining, a five-axis OMAG Blade5 NC900 bridge saw and milling machine with diamond-coated 81cm diameter circular saw blade was used to cut the stone (Figure 16). Such processing was preferred to milling tools, which would have taken significantly more time[15]. No mortar was used at the interfaces between adjacent

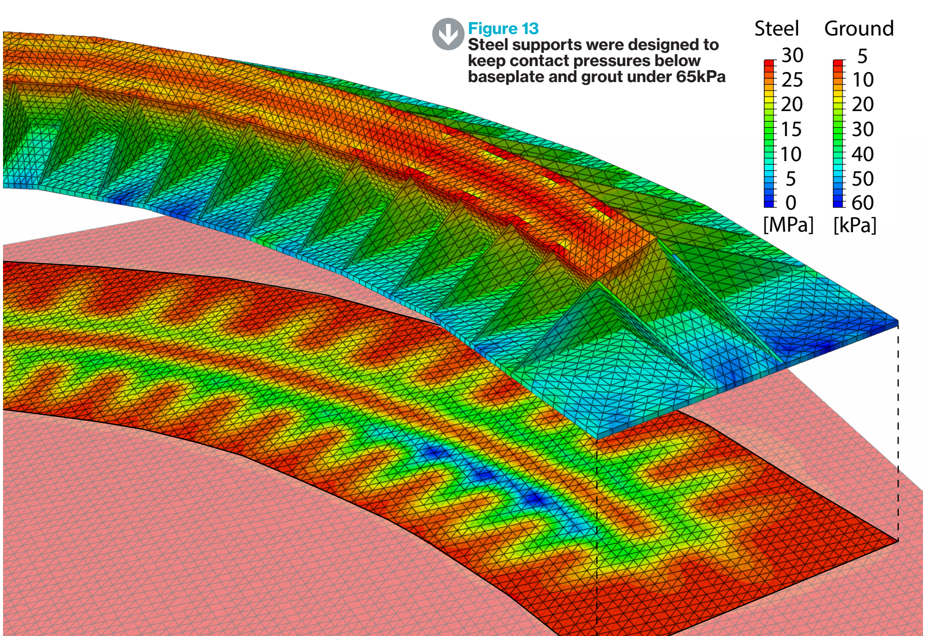


Figure 13
Steel supports were designed to keep contact pressures below baseplate and grout under 65kPa

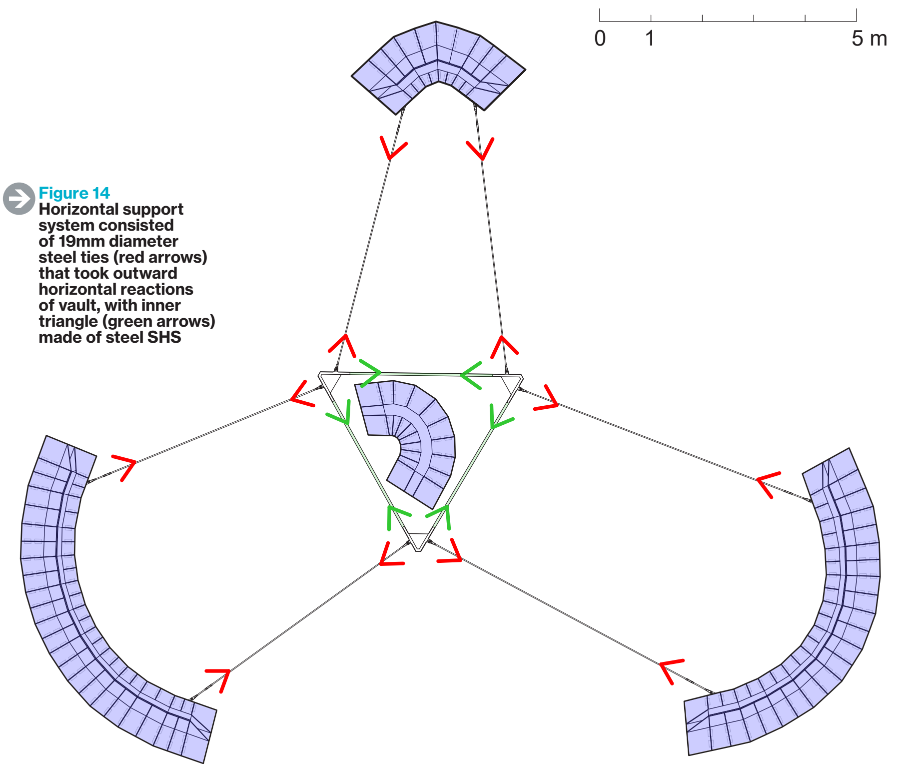


Figure 14
Horizontal support system consisted of 19mm diameter steel ties (red arrows) that took outward horizontal reactions of vault, with inner triangle (green arrows) made of steel SHS

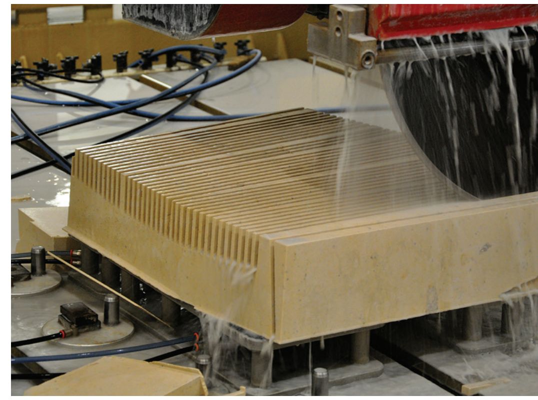


Figure 16
Five-axis CNC machine with circular saw blade was used to make straight cuts into stone, with no time-consuming post-milling of intrados surface

Figure 17
After stone had been cut, resulting fins were hammered off by hand, creating final rough finish

blocks, meaning that accurate cutting was critical, as tolerances could not be catered for during erection using mortar. Tolerances on the cutting machine were allowed to be in the range of 0.4–0.8mm, with the finished voussoirs needing to satisfy tolerances within 0.75mm.

The extrados surface was intentionally kept planar, as producing cuts on both the intrados and extrados sides would have required the stone to be turned over and precisely repositioned before cutting the other side. Instead, the intrados was left responsible for providing double curvature to the vault by cutting parallel channels into the intrados side and breaking off the resulting fins with a hammer (Figure 17). By controlling the blade orientation when creating these channels, it was possible to manipulate how the fins would break off, and so influence the visual qualities. The intrados surface was not milled to a smooth finish, as this would have taken additional time, but the rough surface was instead celebrated by organising the channels to match the force flow, as described previously.

Figure 15
Detail of inner triangle, showing SHSs and plated nodes at corners

The Armadillo's voussoirs transfer the internal compressive forces across the interfaces through the normal contact reactions and stay seated in place due to the mechanical keying of each block. It was calculated that the forces that could be mobilised between voussoirs would be sufficient for any accidental pushout of any voussoir. Half-cylinder joints were created with a diamond-coated profiling tool of 12mm diameter to act as important registration points during erection, as well as providing additional shear capacity for safeguarding against potential seismic loads (Figure 18). When a registration point was not needed, a plain cylindrical tool was used to finish the side faces. Further detailed information on the stone-cutting process can be found in Calvo Barentin *et al.*[16].

Formwork and erection

The preparations for the steel supports began with the placing on the floor of plastic sheets and shims over the baseplate areas, so that the subsequent grouting would

Figure 18
Male and female registration notches, viewed from intrados side, were created for positioning of voussoirs during erection and to provide additional shear capacity for potential seismic events

Figure 19
Shims and grout formed levelled surface for steel supports

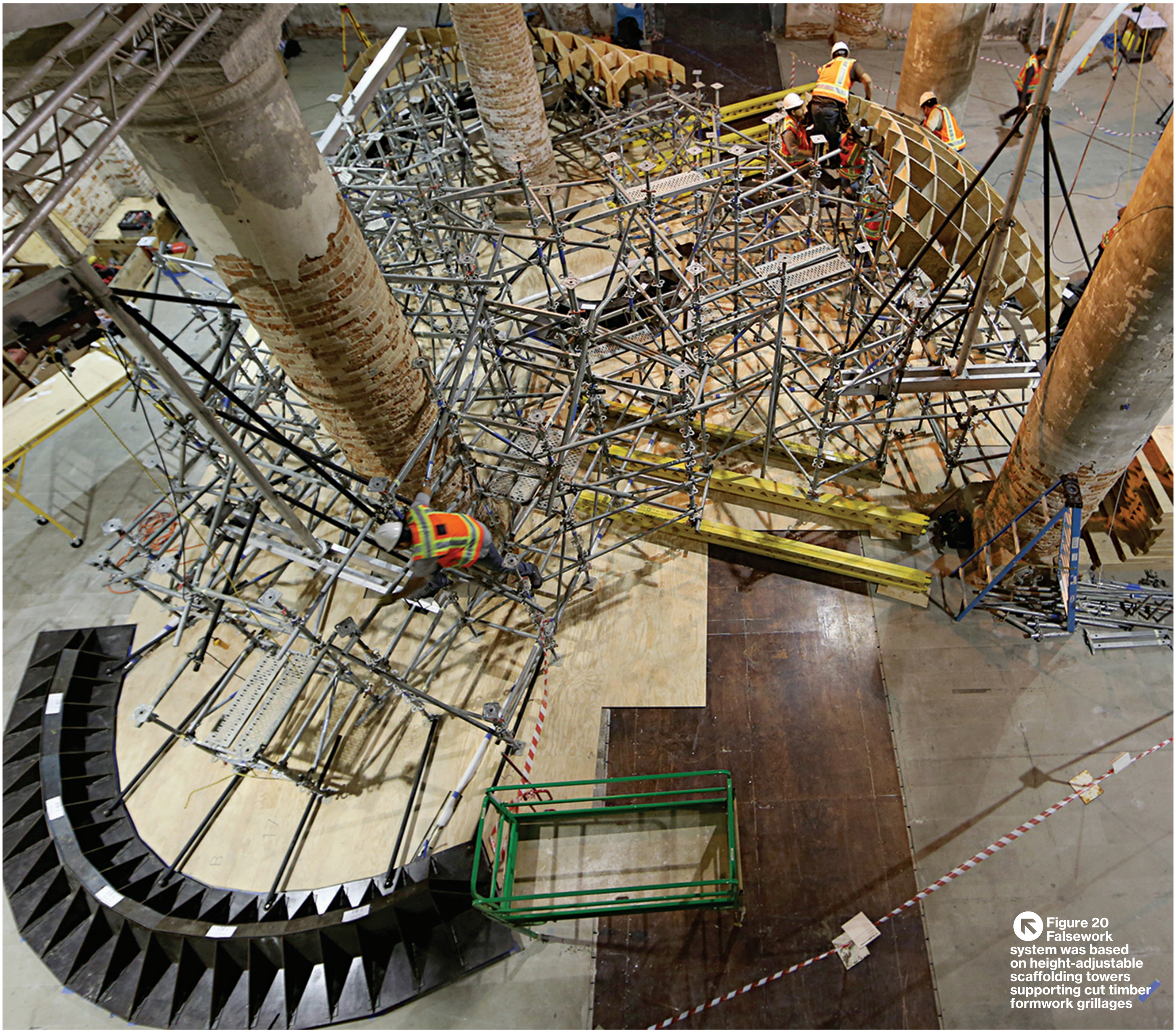


Figure 20
Falsework system was based on height-adjustable scaffolding towers supporting cut timber formwork grillages

Figure 21
Setting voussoirs in place onto falsework using lightweight jib cranes

not adhere to the floor's top surface. The levelled grout surface also served a key structural function, as a structural thickness to help redistribute stresses from the vertical reaction forces (Figure 19).

The falsework consisted of height-adjustable steel scaffolding frames, with timber formwork grillages cut to match the curved shape of the intrados from the digital geometry (Figures 20 and 21). The loads imparted onto the ground during the erection sequence, caused by the falsework, workers and hoisted voussoirs, were all checked so that the contact pressures under the baseplates remained within limits. Due to the absence of heavy machinery to avoid excessive loading on the floor, a combination of scaffolding elements and simple hoists was used, reflecting traditional masonry construction techniques without modern site plant.

The vault was assembled from the supports upwards until a line of keystones was left. These keystones were needed because, despite the best efforts to keep the fabrication and erection as accurate as possible, deviations from various sources would still arise between the as-built and target digital model. The final keystones were not pre-cut, as it would not have been known in advance how all of the tolerances would accumulate. Instead, they were cut only when all other voussoirs were in place and measurements for their required geometries had been taken, so that these keystones would fit perfectly. Wooden shims were used to place and align the voussoirs on the falsework, offset to account for the surface geometry of the intrados.

Once the keystones had been placed into position, the decentring process could begin by lowering the falsework towers in a predefined order with increments of 0.5mm. During this process, after a couple of turning rounds on the adjustable scaffolding, the shims began to fall from the formwork, indicating that the self-weight of the vault had transferred from the falsework into internal forces within the structure. Once the entire weight of the vault had been shed from the falsework, the timber grillages were removed piece by piece and the erection was complete.

Conclusions

The Armadillo vault is an example of using efficient form to create an elegant and stiff structure acting in compression (Figure 22). The vault covered a large area of the exhibition space, with a thinness that was both exciting for the visitors to be underneath, but also necessary to reduce excessive loading on the historic floor. The project demonstrated that a compression-only masonry structure with a high span-to-thickness ratio can be made by utilising geometric stiffness through double curvature. A plated steel support-and-tie system was made, which successfully distributed the self-weight loads of the vault to the ground and equilibrated the structure from the horizontal components of thrust.

The challenges that arose through various constraints were embraced, and resulted in a unique structure that was designed, fabricated, transported between continents and then erected on time and within a tight timespan. Effective computational input led to efficient use of cutting machine resources, which in turn gave a special character to the intrados and extrados surfaces through the solutions that were found. Creating an unreinforced and mortar-less masonry structure demanded care with the design of the vault and keeping within tight fabrication and construction tolerances.

Such a project would not have been possible without embracing digital methods of design and fabrication, without close collaboration to draw on the various skills of the design team, and without the experience and expertise of the construction team.

Acknowledgements

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Structural engineering: Ochsendorf DeJong & Block
Fabrication and construction: The Escobedo Group
Lighting: Lichtkompetenz, Artemide
Sponsors: Kathy and David Escobedo; Department of Architecture, ETH Zurich; School of Architecture + Planning, MIT; Pro Helvetia; Artemide

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Figure 22 Completed Armadillo vault ready for visitors to Venice Biennale