

Innovative funicular tile vaulting: A prototype vault in Switzerland

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Synopsis

This paper presents advances in funicular tile vaulting, made possible through innovation in form finding, falsework systems and construction methods. A full-scale prototype has been realised with the application of new research in the following areas: newly developed structural design tools based on Thrust Network Analysis (TNA), which allow one to generate novel shapes for funicular (compression-only) structures; an efficient digitally fabricated cardboard falsework system, which provides accurate description of a complex reference surface in space; and adaptations of traditional tile vaulting techniques, which have introduced strategies for generating continuous tiling patterns, non-uniform vault thickening, and construction sequencing for structural stability. The methods described in this paper, as applied for the design and construction of the prototype vault, have offered new insights to the challenges of new funicular form for masonry and have paved the way for future research and applications.



Figure 1

Tile vault prototype at ETH Zurich, Switzerland (7.5m x 5.5m x 1.75m high, 28.6m²)

Introduction

This paper presents advances in funicular tile vaulting, which have culminated in the construction of a full-scale vault prototype. The prototype has been realised with the application of new research in three-dimensional structural form finding, a cardboard falsework system, and innovative shell construction methods for masonry vaulting with complex geometry. This combination of newly applied methods and adaptations of traditional tile vaulting techniques will be presented, along with the detailed design of this state-of-the-art prototype.

Tile vaulting, also referred to as 'thin-tile', 'timbrel' or 'Catalan' vaulting, is a 600-year-old Mediterranean construction technique. From the 15th century it was applied frequently all over the Mediterranean, primarily in Spain, but also in areas in Italy, France, Portugal and Algeria; its first application has been recorded in Valencia in 1382¹. The technique, revolutionary at the time because of its extreme economy of materials and speed of construction compared to traditional vaulting techniques, became better known thanks to impressive works by architects and builders such as Antoni Gaudí, Lluís Muncunill or César Martinell in Spain, and the Spanish immigrant Rafael Guastavino and his son in the USA,

who were responsible for over 3000 buildings, among which included several important historic landmarks such as the Boston Public Library and New York City's Grand Central Terminal¹. Recently, there has been an international revival of tile vaulting due to the possibility the construction technique offers to build resource-efficiently and with local materials. Particularly interesting recent projects are the Pines Calyx conference centre in Dover, England, built in 2006 using local chalk tiles², or the Mapungubwe Interpretive Centre in South Africa, finished in 2009, which uses cement-stabilised soil-pressed tiles, produced using only manpower^{3,4}.

Tile vaulting employs a lightweight sandwich of typically three layers of thin (15–25mm) structural tiles to efficiently span space in compression. The rapid-setting (5–20s, depending on environmental conditions) gypsum mortar (plaster of Paris), used to set the first layer of tile, reduces the requirement for formwork by enabling masonry to build in space temporarily unsupported (typically only a few cantilevering rows, depending on the chosen tiling pattern). This first tile layer then becomes a permanent formwork for the rapid construction of the other tile layers which are applied using a normal cementitious mortar.

Key research contributions

The shape of the prototype vault (Figure 1) was defined using the interactive software implementation RhinoVAULT^{5,6} of Thrust Network Analysis (TNA)^{7,8}. This three-dimensional form finding tool allows the generation of novel 'free-form' shapes for funicular, compression-only structures. By controlling a set of boundary conditions, such as the general shape in plan, the shape of open edge arches, the location of footings and the internal distribution of thrusts, which directly influences the articulation of the surface, a form was generated which is a fully three-dimensional equilibrium solution for the vault's self-weight. This prototype served to validate the TNA form finding methods, and to demonstrate its potential for the creation of novel and expressive funicular forms (see 'Form Finding Method').

The vault was built with the application of an efficient cardboard box falsework system, which allowed for the accurate description of the complex surface obtained with the TNA form finding. Fabricated out of flat-sheet cardboard, cut using 2.5D Computer Numerically Controlled (CNC) cutting technology, the resulting boxes were assembled together rapidly on site to approximate the doubly curved surface, which served as a spatial guide for laying the masonry. In the absence of such a falsework system, it would be virtually impossible for masons to follow the shape of such geometries. As the falsework system also had load-bearing capacity, it was able to support the vault to some extent in intermediate stages during construction, allowing for certain layouts of tiles not possible in traditional tile vaulting (see 'Falsework System').

Traditional tile vaulting techniques have been adapted to address the challenges of complex doubly curved geometry, but also to enhance its aesthetic qualities. New strategies were introduced to achieve continuous tiling patterns, high degrees of curvature, and visually non-obstructive local thickening of the vault. The graphical results of the form finding process also allowed for structural information to be transmitted to the vault builders in an understandable and direct fashion (see 'Shell construction methods for complex tile vaulting').

The vault's 28.6m² surface (7.5m by 5.5m, with a maximum height of 1.75m) was constructed within a 6-week period by a construction crew of (on average) two people, demonstrating that the benchmarks of economy of tile vaulting, in both material and cost, are possible for complex geometries (see 'Economy of construction').

Figure 2a
TNA form finding method: force network in plan

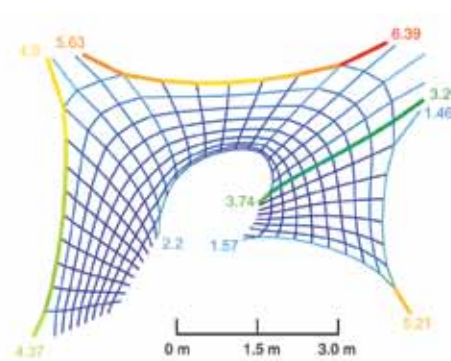


Figure 2b
Corresponding reciprocal force diagram

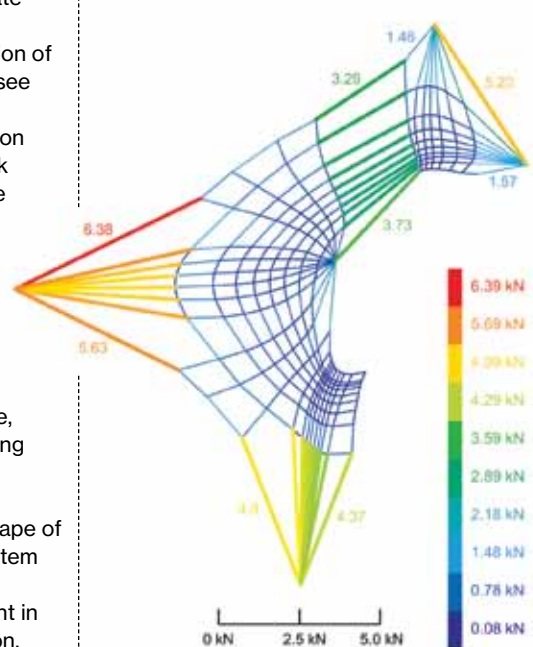
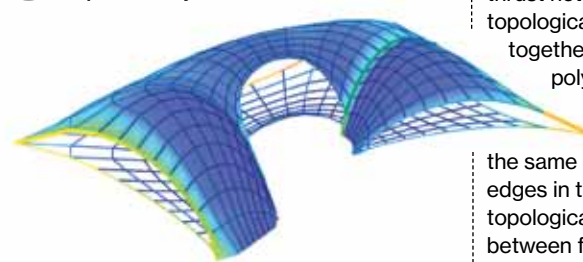


Figure 2c
Compression-only thrust network



"An overview of the different components used in TNA is shown in Figure 2"

Process

Form finding method

Thrust Network Analysis

Thrust Network Analysis is a recently developed form finding method for the design and analysis of compression-only vaulted structures with complex geometry. To provide a graphical and intuitive approach, TNA uses geometrically linked form and reciprocal force diagrams⁹. Similar diagrams are used in graphic statics^{10,11}, but TNA extends their application to fully three-dimensional problems. The TNA method provides the user with a high level of control over the force distributions in a funicular network, in order to accomplish a given design goal. The structural design process involves the interactive, bi-directional and weighted manipulation of the form and force diagrams, which allows for the translation of design-driven constraints to exciting equilibrium solutions.^{5,12}

An overview of the different components used in TNA is shown in Figure 2. The form finding method employs a) a form diagram with scale in metres, defining the plan geometry of the structure and the force pattern, laid out by the designer; b) its corresponding reciprocal force diagram, which represents and visualises the distribution of horizontal thrust to the relevant scale in kN; and c) the resulting compression-only *thrust network*, in equilibrium with given loading - in this case the self-weight of the vault.

The reciprocal force diagram (Fig. 2b) represents the in-plane equilibrium of the form diagram (Fig. 2a), and, because the design loads (gravity loading from the vault's self-weight) are all vertical, so too is the horizontal equilibrium of the resulting thrust network (Fig. 2c). The edges in this topologically dual diagram (edges coming together in a node corresponds to a closed polygon in the other diagram, and vice versa) to the form diagram are all parallel and orientated in

the same direction to their corresponding edges in the form diagram. It is this strict topological and geometrical relationship between form and force diagram that guarantees in-plane equilibrium⁹. Indeed, one can recognise that the equilibrium of each node in the form diagram is represented by a closed vector polygon of forces in the force diagram. That each of these polygons can be joined to form the force diagram means that global equilibrium is satisfied. As a result, the thrusts in each edge of the form diagram (respectively the thrust network) can directly be measured from the force diagram, which is drawn to scale (Fig. 2b). Note that the reciprocal diagram shown in Fig. 2 is the result of the interactive form finding process

and represents the equilibrium of thrust of the final shape used to build the prototype.

The built prototype has a dead load of approximately 1.1kN/m^2 . Using the graphical information provided by the form and force diagrams together with the geometry of the resulting thrust network, all reaction forces at the supports could be calculated easily, by measuring and using simple trigonometry. The labelled values in the form and force diagram show the magnitudes of horizontal thrust in areas with higher force concentration. Measuring the reciprocal edge length, multiplied by the scale, thus allowed the definition of the thrust in each branch of the thrust network. Based on this information, the sequencing of the tiling patterns, the design of the footings and the local thickness of the prototype vault were directly informed (see 'Shell construction methods for complex tile vaulting').

Interactive form finding with RhinoVAULT

A user-friendly and interactive implementation of TNA allowed for a smooth, structural design process. The form finding tool RhinoVAULT was developed for and tested in the design process of the prototype vault. Implemented as a plug-in for the CAD software Rhinoceros¹³, a program well-established among architects and structural designers, it facilitates the intuitive control over the form and force diagram to steer funicular form.

This tile vault prototype has offered the unique opportunity to test the form finding tool on a large-scale project, along with the challenges presented in design and construction of a compression-only structure of such geometry. The maximum height, surface area and enclosed volume were mainly driven by constraints of site and schedule. Both technical and aesthetic criteria aimed for a light and open form,

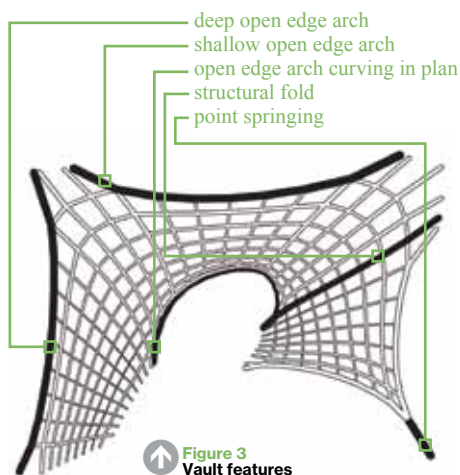


Figure 3
Vault features
Note: The different thicknesses of edges are proportional to the horizontal thrust in the structure under self-weight

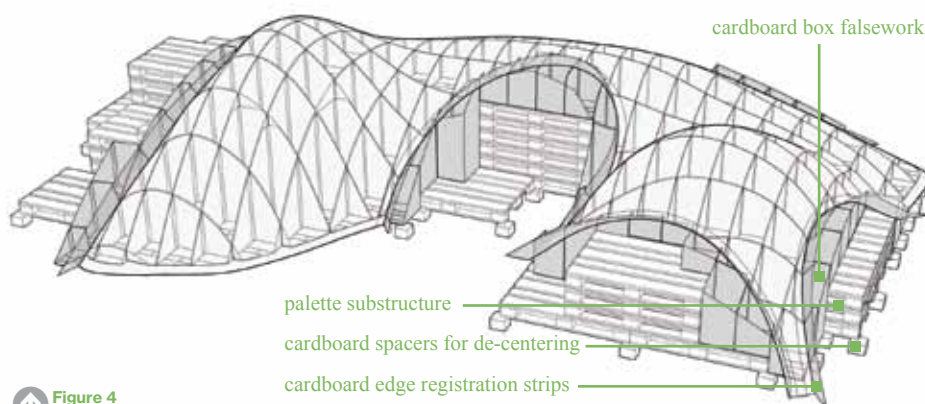


Figure 4
Falsework assembly

which included multiple 'open edge' arches, a point support and high degrees of curvature. Other guidelines for the design included falsework constraints and suitability for possible tiling patterns.

Different boundary conditions and structural features were designed (Figure 3).

The structural fold feature very convincingly demonstrates the control enabled by the TNA approach: by stretching a section of the force diagram, while maintaining the parallel and directional relationship (this is enforced by RhinoVAULT), forces are locally increased in that region of the vault surface, creating the undulation in the compression-only thrust network.

Falsework system

Cardboard box falsework

The range of complex geometries for equilibrium vaults enabled by TNA gives rise to a new class of funicular tile vaulting, which also present new challenges with respect to construction processes. A mason must know where to place bricks, anticipating the geometry of the doubly-curved surface in a controllable and accurate manner. It should be kept in mind that the thin, compression-only, tile vaulted shell (only 90–140mm thick) must be accurately laid to guarantee the stability of the structural form and to avoid its geometrical safety factor being reduced¹⁴. For traditional tile vaulting it is typically sufficient to use simple and sparse geometric guides, for example light timber slats mounted on frames. A trained mason can then easily interpolate the form in space between these. For these new complex forms though, such an approach is no longer sufficient to aid the builder in the execution. A surface guide is needed to describe the complex doubly-curved masonry surface to the mason.

The cardboard box falsework system employed for this research (Figure 4) has offered a solution for this challenge. This assembly of boxes, palettes and spacers

provides a comprehensive registration surface with sufficient resolution for constructing the surface generated with the TNA form finding.

As shown in Fig. 4, an assembly of shipping palettes provides the first rough approximation of the vault shape. This reduces the volume of cardboard needed and facilitates easy access during construction with a step-like configuration. The CNC-cut cardboard boxes are then aggregated over this palette substructure to form a surface guide of sufficient resolution. The use of the smaller boxes increases the resolution of the surface and therefore refines the visual surface guide for the masons, allowing for the surface curvature to be built more accurately with respect to the generated TNA compression surface. The box dimension (600mm x 400mm x 400mm) has been selected based on its relation to the brick size, the compatibility with the dimensions of the palettes, and requirements for access by the mason, i.e. the box dimensions allow bricklayers to stand inside of the open boxes, rather than on their edges.

Computer-aided design and manufacturing

Since the falsework was developed from the TNA surface, its design and fabrication may be considered as an extension of the digital workflow enabled by TNA¹⁵. A series of customised software tools were used to translate this output surface into the assembly of discrete palettes and boxes, with attention to both the optimisation of construction material and the machine constraints of the fabrication process. A customised cutting pattern was automatically produced for each of the unfolded boxes.

Figure 5 shows the design and production process for the boxes, established by a digital workflow¹⁶, using customised algorithms to translate the compression surface into the final machine code needed

to produce the 216 individual cardboard boxes. The algorithms define the positions of the palettes, arrange the cardboard boxes, establish naming and labelling conventions, organise the CAD document, crop the boxes with the vault surface, unroll the 3D geometry of each box, identify the curves for cutting, creasing and labelling, identify unexpected exceptions, monitor the position of the 2D labelling, and query the user for its optimisation. Ultimately, the final tool paths for a maximum of two boxes are nested on single cardboard sheets, and the translation of the tool paths to the final machine code is completed with a custom CAD-CAM interface.

As the cardboard falsework system had a structural capacity of 5.5kN/box, or 6kN/m², and the average self-weight of a tile vault was quite low (1.1kN/m²), the falsework could also be employed to support unfinished sections of the masonry vault during construction, before closing them to form a stable section.

Shell construction methods for complex tile vaulting

The new range of shapes made possible by TNA, and further facilitated in construction by the cardboard falsework system, call for some adaption of traditional tile vaulting techniques. New construction strategies, addressing masonry tiling patterns, construction sequencing, curvature control and structural thickening, were developed in relation to the structural force diagrams, thus effectively linking traditional construction methods and new form finding tools.

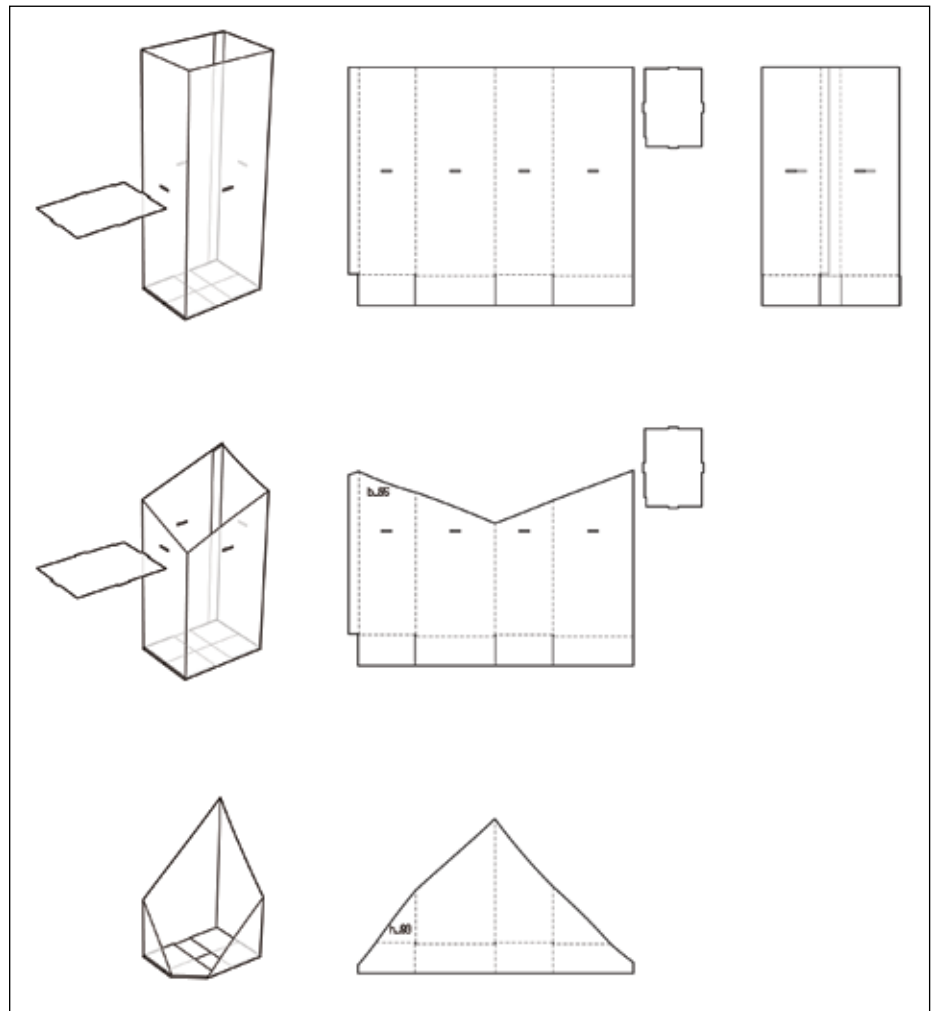


Figure 5a
Cardboard box fabrication: customised CNC cutting patterns



Figure 5b
Assembled falsework box



Figure 5c
Fabrication process using a CNC controlled cutter

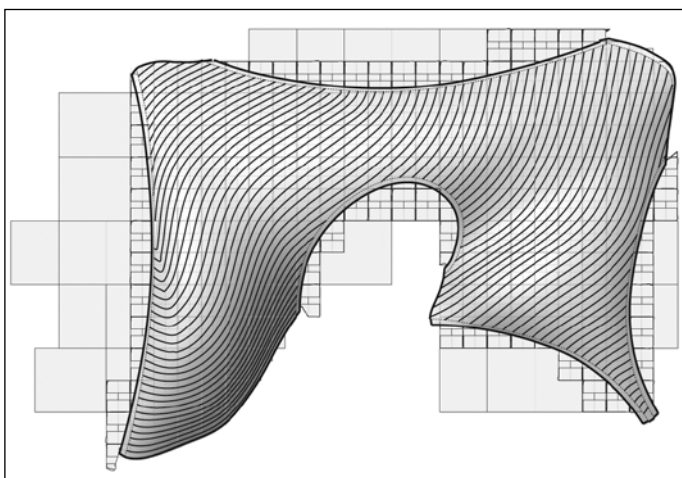


Figure 6a
Continuous tile patterns: first layer

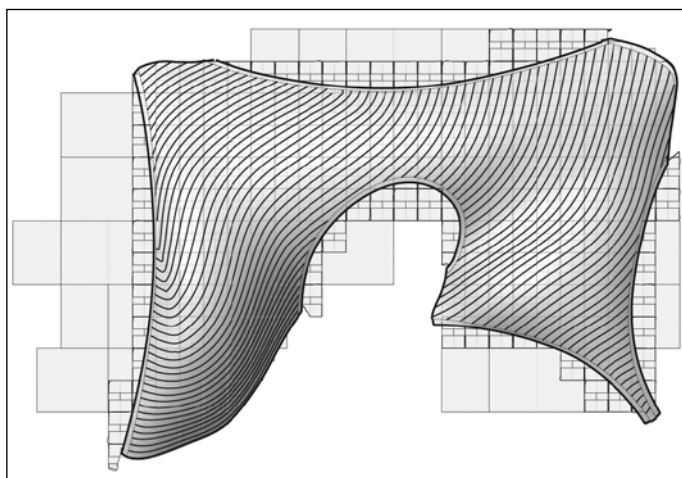


Figure 6b
Second layer



Figure 6c
First layer during construction



Figure 6d
Second layer after completion

Continuous tiling patterns, sequencing and stability

The use of a rapid-setting, gypsum mortar (plaster of Paris) for the first layer of tile vaulting allows shells to cantilever short distances (typically only a few rows of tiles)¹⁷, counting on small amounts of bending until a stable section of the shell surface is closed, at which point the load is carried in compression. As a result, the tiling layout must be chosen such that it is able to be built in structurally stable sequences, such as arches or hoop rings in domes.

The cardboard falsework had some load-bearing capacity however, and as such it could support the vault at interim stages of construction. Thus, the falsework system mitigated the need to sequence masonry courses in stable sections during construction. For this reason, it was possible to develop continuous tiling patterns, which

traditionally would not be possible in tile vaulting where proper sequencing logics need to be respected. Although allowing for new possibilities and applications, this strategy clearly goes against one of the key benefits of tile vaulting: that only very minimal form- and falsework is needed for its construction.

If the presented vault were to be constructed in the conventional manner, one would need to first construct single arches, e.g. along the creases, on full formwork, thereby dividing the compression form into nicely positively doubly-curved shell segments, which could then be built up by filling in the surface - for example from the corners inwards. Such a strategy however, would make little sense structurally, on account of the fully three-dimensional equilibrium design of the vault. Perhaps just as importantly, such patterns would

visually disrupt the flowing three-dimensional 'free-form' shape, thereby undermining the purpose of the research.

In Figure 6, the continuous patterns intended for the first and second layers of masonry are shown, which are set with a fast-setting Plaster-of-Paris (Formula Hartform 1 gypsum)¹⁸ and a typical cementitious mortar, respectively.

Note that coordination between the tiling patterns of the first and second layer is also necessary to prevent joints from aligning. This is reasonably simple to achieve for the regular geometries of traditional vault types (typically by rotating the pattern of the second layer by 45°). However, tiling patterns which follow shapes of a 'free-form' appearance, require careful coordination to minimise unavoidable local pattern alignments, which would weaken the bonded layers of structural tile.

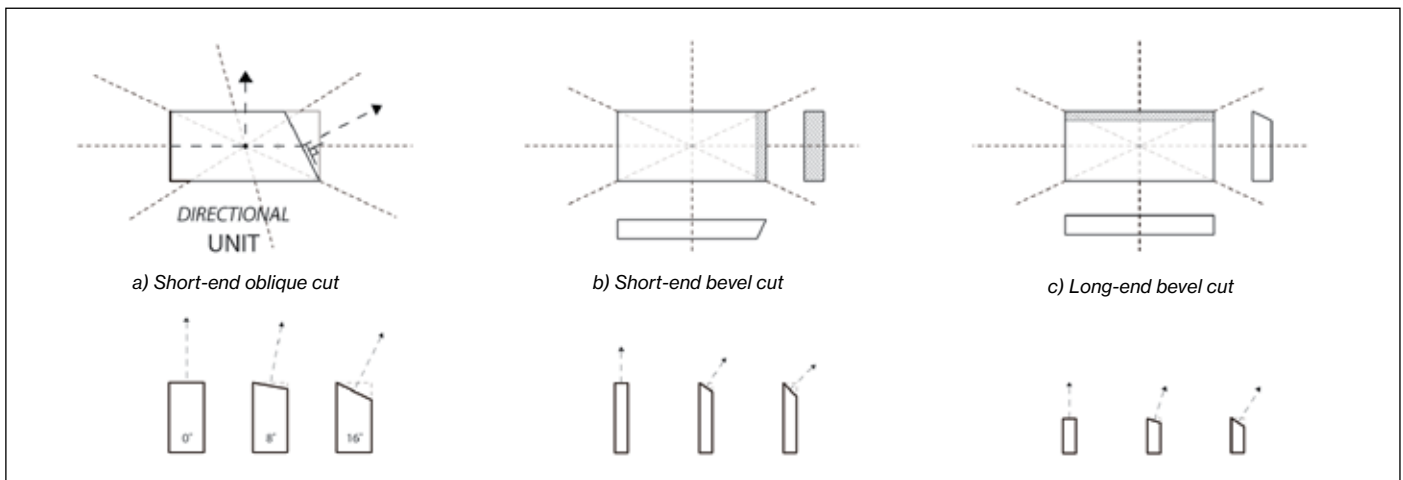


Figure 7
Brick primitives for the one-cut and two-cut systems

Curvature and cutting logic

To achieve high degrees of double surface curvature with orthogonal masonry units, it is necessary to custom-cut the bricks. This is needed to facilitate multiple directional hinging of the masonry units to achieve high degrees of curvature without having to compensate excessively with the mortar joints. The capacity for realising curvature with tiling is dependent on the relationship of the scale of the masonry unit and the scale of the vault. Thus, while the following strategies have provided a solution for the extreme curvature resulting from the scale of the prototype vault, larger structures would be expected to mitigate this challenge. The concept of cutting the tiles to achieve large degrees of curvature is of course not new. Gaudí for example cut tiles along the diagonal to realise the beautiful hyperbolic paraboloid Catalan vaults in the Sagrada Família in Barcelona¹⁹.

The cutting strategies for the prototype construction were based on previous research of one- and two-cut cutting systems²⁰, which employ three brick primitives: a) a short-end oblique cut, b) a short-end bevel cut, and c) a long-end bevel cut (Figure 7). The most ideal cutting logic for the high double curvature of the prototype vault would have been the two-cut system, which involves the use of combination cuts to 'bend' a surface more effectively in space. The more simplified one-cut system (using only cuts of the type shown in Fig. 7a) was instead used, predominantly on account of the limitations of available masonry cutting tools. This allowed for high degrees of curvature in one axis of the masonry unit, while relying on hinging and compensation by the mortar joint along the other axis. The two-cut system was only implemented in the regions of greatest curvature e.g. at the structural fold (Fig. 3).

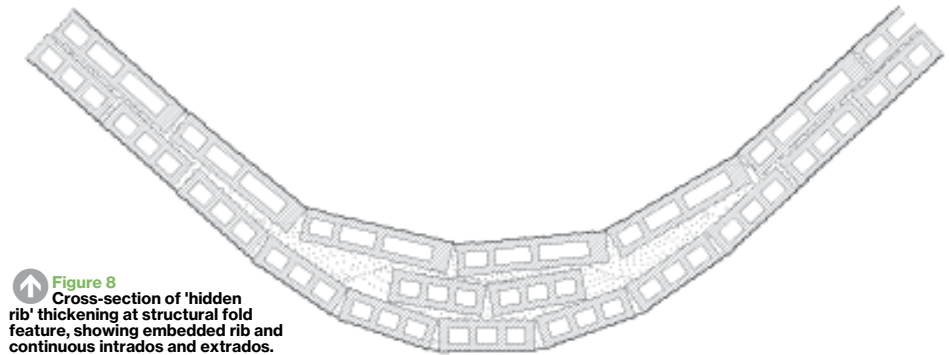


Figure 8
Cross-section of 'hidden rib' thickening at structural fold feature, showing embedded rib and continuous intrados and extrados.

Non-uniform vault thickening

Since three-dimensional equilibrium structures have non-uniform force distributions, the prototype vault provided the opportunity to express this with a non-uniform thickness, thereby reducing stresses. To maintain a continuous surface curvature, while thickening the shell only locally in areas where higher forces were attracted, a third layer of tile was sandwiched between the intrados and extrados tile layers, hence also hiding the local thickening of the vault. This approach was inspired by the V-beam thickening strategies used in concrete shell construction by, amongst others, Félix Candela at the Los Manantiales Restaurant at Xochimilco, Mexico City²¹. This 'hidden rib' thickening, tested in the prototype shell, provides continuity of the vault's intrados and extrados surface from both a structural and visual standpoint (Figure 8).

Vault thickening details were directly developed using the graphical information provided by the form and force diagram (Fig. 2). By keying directly from these diagrams, the mason was able to easily translate this structural information to the construction. Note that the longest branch lengths in the

force diagram are the areas with highest thrusts, which was where increased cross-sections were used. A hidden rib has been applied in two regions where higher forces are concentrated in the vault: the edge arch of lowest rise and widest span, and the structural fold (Fig. 3). It is clear that for a vault of this size, the local thickening of the vault was not necessary. The maximum stresses, assuming two layers of tiles, are only 0.77MPa, which is almost two orders of magnitude below the compressive strength of the tiles; these maximum stresses occur at the top right support of the longest edge arch (Fig. 3). This prototype was intended to test new ideas, relevant to building complex geometries, and this thickening experiment was thus only intended to demonstrate new possibilities, rather than out of structural necessity.

Figure 9a shows the hidden rib during construction, as the third layer of tile is being sandwiched locally between the continuous intrados and extrados. Figure 9b shows an alternate thickening strategy employed in the prototype, which involved the use of local stiffening diaphragms, achieved by placing tiles on their side between two layers of vaulted surface. This allowed for

a) Spacer and palette assembly



b) Box installation and footing preparation



c) First layer masonry



Figure 10
Construction sequence

Construction sequence

The construction sequence may be simplified to that shown in Figure 10.

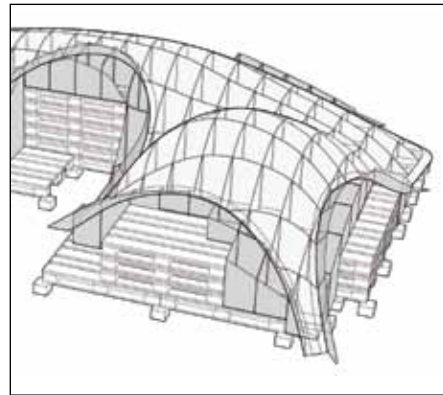
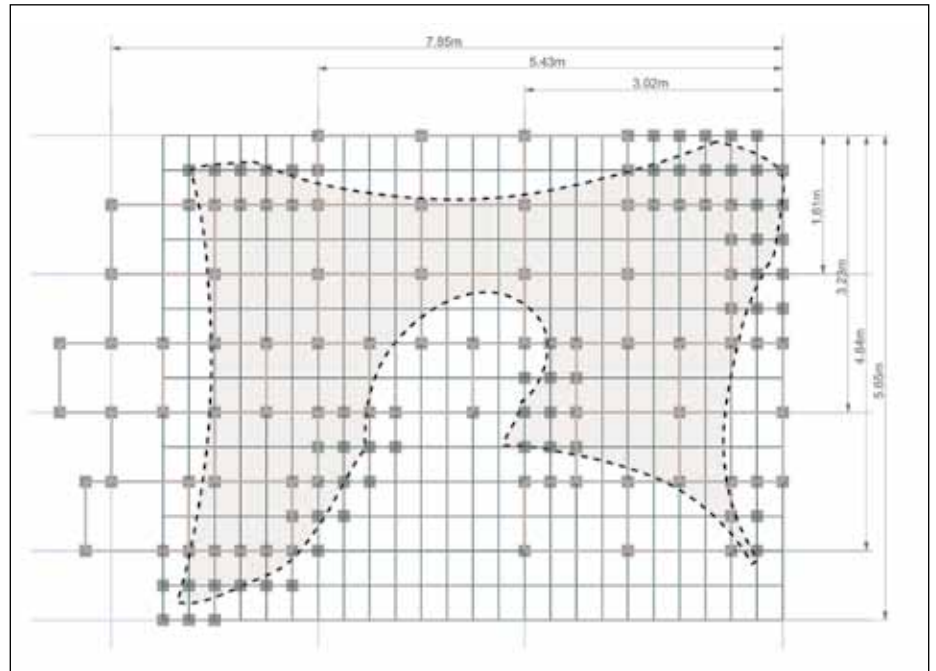


Figure 11a
De-centring spacers: Detail of falsework system

Figure 11b
Plan drawing of cardboard box/palette falsework assembly with de-centring spacers



De-centring mechanism

For funicular shells, the removal of formwork, i.e. the de-centring of a vault, must proceed evenly to avoid asymmetrical loading of the shell from below, which could induce bending and potentially cause cracking or even collapse. The falsework for this prototype was used to carry load during construction, so it was critical to ensure even de-centring. The supporting structure of discrete boxes and palettes was anticipated to be difficult to lower uniformly, and a low-tech solution was thus introduced to address this challenge. The entire box and palette assembly was built on cardboard spacers, sealed with plastic tubes running the length of the assembly (Figure 11a-b). After completion of the vault, these tubes were filled with water, causing the non-water-resistant cardboard glue to dissolve, the spacers to steadily compress under the weight of the palettes, and the entire assembly to lower slowly and uniformly. The palettes could be subsequently pulled out and the boxes removed (Figure 11c). The dry



Figure 9a
Vault thickening strategies during construction: Hidden rib at structural fold



Figure 9b
Diaphragms at point springing

a much deeper cross-section at the point springing of the vault, where the vault would have been particularly vulnerable to asymmetrical loading, respectively buckling. While diaphragms are commonly used in traditional tile vaulting, they are not as commonly sandwiched between two layers of vaulted surface. A historical example of this lightweight constructional solution to increase the structural depth are the undulating shells of the Aymerich, Amat and Jover Factory by Lluís Muncunill in Terrassa, Spain, 1908.



compressive load capacity of the spacers was calculated to carry the load of the palette/box system, an estimated loading of the masonry vault during construction and the live-loading of the masons. Tests were conducted to insure that the cardboard spacers could carry this loading in a dry state, while compressing under the load of the palettes in a saturated state (Figure 11d).

Figure 11c
Plan drawing of
cardboard box/palette
falsework assembly with
de-centring spacers

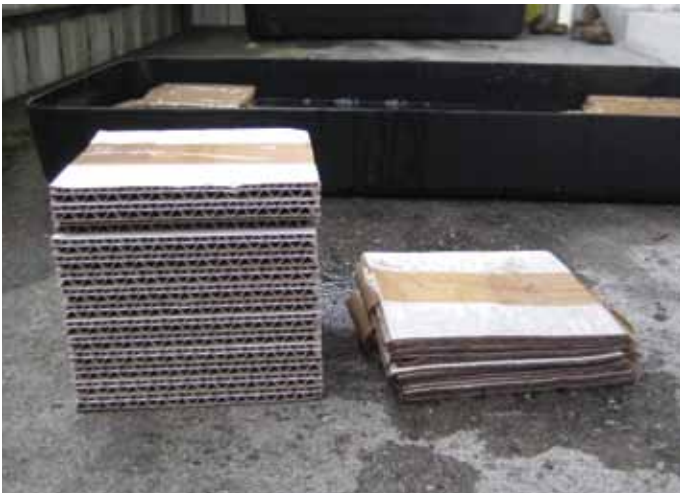


Figure 11d
Cardboard de-centring elements in only
load-bearing and saturated, compressed states

Structural load testing

The load-testing of the vault proceeded with the application of a patch-load, applied over an area of 500mm by 500mm, using stacked sand bags (Figure 12a-b). The position was chosen to be at the quarter-point of the edge arch with lowest rise and widest span (Fig. 3). For practical reasons, the experiments had to be stopped after applying an accumulated load of 3 tons. At this point, there was no visible cracking, measured displacements or movements in the vault and at the supports. SMARTEC MuST FBG Deformation sensors²³ were utilised for the monitoring of the deformation in selected sections of the structure, but unfortunately no useful data was generated.

It should be noted that the prototype construction did not have proper foundations, because it was meant to be a temporary installation. According to the positions of greatest horizontal thrust indicated by the force diagram, steel stakes of 500mm were provided at the footings to prevent abutment sliding. While this strategy proved to be sufficient for construction and structural loading, the footings were carefully observed for displacements throughout all phases.



Figure 12a
Load test: Application
of patch loading (3 tons)

Discussion

Challenges in construction

Sequencing and stability

In practice, the masonry unit was too coarse with respect to the degree of surface curvature for the first layer to effectively touch the formwork in all places. Small amounts of bending were thereby induced in the shell, which slightly exceeded the capacity of the gypsum mortar, as evidenced by local hairline cracking during an early phase of construction. This presented challenges in the control of interim-state structural stability with the falsework. It was thus necessary to slightly modify the continuous tiling pattern in the first phase of construction, and to carefully sequence masonry coursing to insure that the load would be efficiently transferred to the supports as quickly as possible (Fig. 6c-d). This was necessary to prevent the shell from cracking and to maintain stability with this particularly complicated masonry pattern.

Quality control

Another limitation of the falsework system involves rather simple concerns of constructability in tile vaulting techniques. During construction, the boxes provided limited access to the underside of the vault, compromising the cleanliness and quality of the mortar joints. More importantly, this prevented masons from assessing or correcting such errors. Post-construction assessment showed that this was particularly problematic in areas of negative double curvature. Where masonry hinges opened downwards, wet mortar had at times slipped out and left open mortar joints through which the compressive forces could not be transmitted.

Economy of construction

Traditionally, tile vaulting is a material efficient construction technique by virtue of its use of good structural form to achieve a minimal vault thickness, and use of minimal, lightweight form- and falsework. While the more complex, new shapes and comprehensive falsework presented in this paper seem to negate the inherent material and labour efficiency of tile vaulting, the cardboard falsework system introduced is capable of describing the 'free-form' tile shell with comparable material economy (Tables 1 and 2). Its rapid fabrication, lightweight transportation, and speed of erection and de-centring dramatically reduced the material and labour-based costs of construction (Table 3). An inexpensive and potentially reusable/recyclable material, this lightweight cardboard falsework extends the economic



Figure 12b
Historical
'inspiration' of
loading a tile vaulted
staircase by Raphael
Guastavino (Source:
Guastavino/Collins
Archive)²²

Table 1: Quantity and weight of masonry

| | |
|--|--|
| Vault surface area | 28.6m ² |
| Vault thickness (2–3 layers) | 90mm–140mm |
| Brick (dimensions; unit weight): ²⁴ | 200mm x 40mm x 120mm; 1kg |
| Quantity: | 2,300 bricks/vault |
| Weight: | 2,300kg = 2.3 metric tons |
| Plaster mortar: | 5mm mortar joint |
| Quantity: | 0.07m ³ |
| Weight: | 101kg = 0.1 metric tons |
| Cement mortar: | 7mm–10mm mortar joint |
| Quantity: | 0.38m ³ |
| Weight: | 926kg = 0.9 metric tons |
| Total weight of masonry: | 3.3 metric tons = 1.1kN/m ² |

Table 2: Quantity and weight of formwork

| | |
|-------------------------------------|---|
| Palettes (dimensions; unit weight): | 1200mm x 800mm x 144mm; 25kg |
| Quantity: | 107 palettes |
| Weight: | 2,675kg = 2.7 metric tons |
| Boxes (dimensions; unit weight): | Custom sizes; 0.7kg/m ² |
| Quantity: | 216 boxes = 158m ² cardboard |
| Weight | 110.6kg = 0.11 metric tons |
| Total weight of formwork: | 2.8 metric tons |

Table 3: Estimate of labour for bricklaying*

| | |
|--------------------------------------|---|
| Average vault construction crew: | 2 workers |
| Total duration of bricklaying: | 340 hours |
| First layer masonry (gypsum) | 186 hours |
| Second layer masonry & ribs (cement) | 154 hours |
| Estimate of labour for bricklaying: | Approx. 21 days for 2 masons (8hrs/day) |
| Estimate of labour/sq. meter: | 11.9 hours/m ² |

*Note: This estimate considers only the brick laying for the first and second layers as well as thickening ribs. Estimate does not include formwork installation or de-centring.

viability of tile vaulting to the construction of these new shapes, with a sustainable improvement upon prevalent falsework or formwork materials (e.g. lumber, CNC cut plywood). Such post-consumer material flows may be considered along with cost factors and labour for a combined result of economy.

Conclusions and future work

This paper has described the structural design and construction of an expressive funicular vault, made possible by coupling novel form finding tools, a cardboard falsework system and adapted construction methods for tile vaulting. While traditional methods of tile vault construction tend to limit the achievable forms and tile patterns, this prototype construction has demonstrated innovations and new possibilities for the tile vault (Figure 13).

The form finding methods based on Thrust Network Analysis have now been verified at full scale through successful construction and structural load testing. Future work is proposed to streamline the TNA form finding process with several aspects of constructability, coupling TNA form and force diagrams more explicitly with tiling patterns and thus also sequencing logics. Such integrated workflow strategies may be employed, for instance, to determine a TNA output surface, which constrains the degree of double-curvature to that achievable by a given masonry unit. More suggestively, by coupling these constructional logics with equilibrium analysis, we may evaluate the equilibrium of structures in all states of construction and reduce the reliance upon continuous formwork supports during construction. Future work also includes the development of guiding systems with less material, perhaps even digital.

The authors believe that the vault described in this paper displays similar formal freedom as shapes derived from purely geometrical design processes, while still exhibiting the desirable traits of a fully

 **Figures 13**
Completed prototype (Source: Klemen Breitfuss)



3D, structurally shaped, compression-only shell. This project demonstrates that free-form, experimental architecture does not necessarily have to mean excessive material use. The combined implementation of low-tech, traditional construction methods and state-of-the-art form finding tools may indeed point the way towards co-design of expressive forms and material resourcefulness.

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