Proceedings of the IASS-SLTE 2014 Symposium
"Shells, Membranes and Spatial Structures: Footprints"
15 to 19 September 2014, Brasilia, Brazil
Reyolando M.L.R.F. BRASIL and Ruy M.O. PAULETTI (eds.)

Thin-tile vault for the Seventh World Urban Forum in Medellin

David López López*, Marta Domènech-Rodríguez[a], Josep Brazo Ramírez[b], Philippe Block[c],

* ETH Zurich, Institute of Technology in Architecture, BLOCK Research Group
Stefano-Franscini-Platz 5, HIL H 46.2, CH-8093 Zurich, Switzerland
lopez@arch.ethz.ch

[a] UPC Barcelona, School of Architecture, Design Department
[b] UPC Barcelona, School of Building Construction
[c] ETH Zurich, Institute of Technology in Architecture, BLOCK Research Group

Abstract

This paper presents a project designed and built for the Seventh World Urban Forum (WUF7) in Medellín, Colombia, commissioned by the Department of Habitat of the United Nations (UN-Habitat).

The project is a "free-form" masonry shell, built using the technique of thin-tile vaulting (also known as Catalan or Guastavino vaulting). UN-Habitat intended this shell to be a demonstration for the technique's efficiency, versatility, durability, sustainability and economy as an example to be exported to developing countries.

The shell's shape was designed using the form-finding software RhinoVAULT, which allows the design of compression-only surface structures. Special care was taken to integrate the vault in its surroundings, a park in an urban area of Medellín. It wanted to be visible, but at the same time also a natural part of its environs. The shell emerges from the earth to shape a new topography featuring a green roof that continues the park's landscape, while showing a surprising brick-patterned interior, creating a warm, cozy space as a contrast to its exterior.

The design process, structural analysis and production of an efficient falsework and the different processes related to the construction are also detailed in this paper.

Keywords: Catalan / thin-tile vault; compression-only / funicular form; structural design; brick architecture.

1. Introduction

The project presented in this paper is a "free-form", semi-buried, unreinforced masonry shell. It was built from March 31st to April 25th 2014 in the Park "Juanes de la Paz" in the northern part of the city of Medellín, in the Department of Antioquia, Colombia. The project is integrated in the park, becoming part of a green area in the urban landscape, surprising the public with an unexpected interior made of brick (Figure 1).

This tile-vaulted project was commissioned to the BLOCK Research Group by the Department of Habitat of the United Nations (UN-Habtitat) to be shown at the Seventh World Urban Forum (WUF7), which happened from April 5th to 11th 2014. UN-Habitat's aim was to further promote this affordable and sustainable building technique, especially for developing world contexts. The shell follows also a series of recent projects that have investigated novel applications and design possibilities for thin-tile vaults (Ramage *et al.* [7]; Davis *et al.* [3]; López López *et al.* [6]; Block *et al.* [2]). The novelty of this project is the use of tile vaulting to integrate semi-buried spaces in a public park, creating a continuity of and elegant interfaces and transitions between the green and paved surfaces, while addressing users' safety and new details needed for it.

Thin-tile vaults are masonry structures made with thin bricks and mortar. The bricks are placed flat, building up two, three or more layers. Traditionally, thin bricks -or thin tiles- are used because of their lightness, which is a necessary condition to build the first layer "in space", so without falsework. Using gypsum or fast-setting cement, the first layer is achieved through the quick adhesion of such mortars. As a result, the bricks stick within seconds to the edge walls, already finished arches or stable sections, taking away the necessity of centering (Huerta [4]). Using this first layer a s a permanent formwork, the second and subsequent layers can be set with lime or Portland cement mortar.

Figure 1: Views of the vault at Park "Juanes de la Paz", Medellín, Colombia. © Sergio González

2. Materials

Three main elements compose the building: the foundation, the vault and the green roof. The foundation is a reinforced concrete slab. The materials of the vault are bricks, gypsum and Portland cement mortar. The green roof is made up of waterproofing and drainage layers, as well as a layer of soil and plants (see Section 5.4. for details of the green roof).

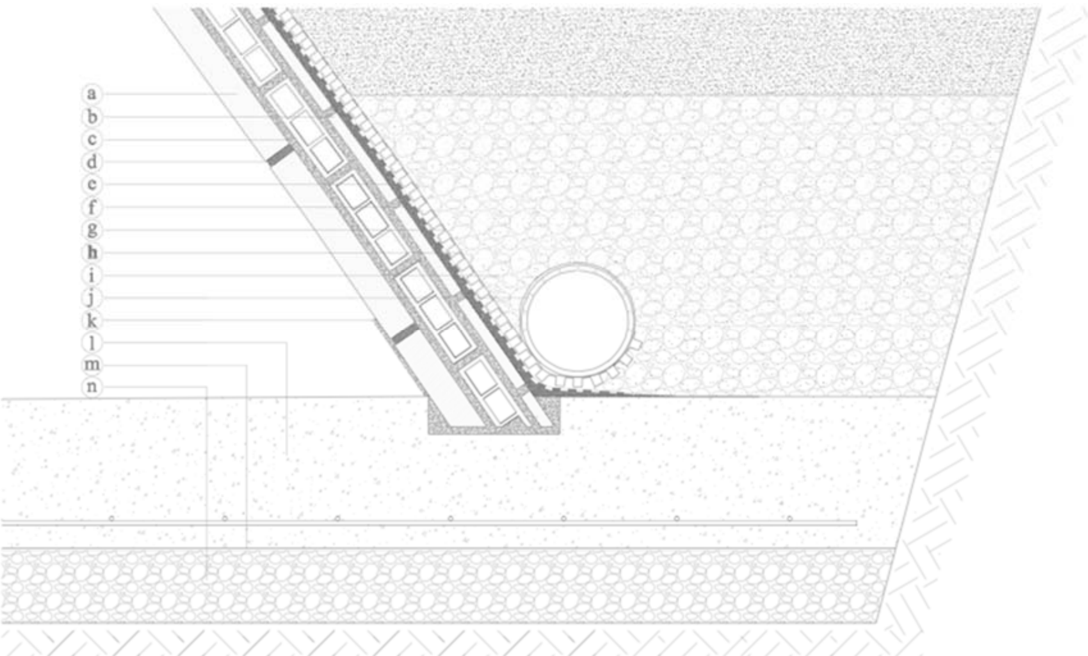

Figure 2: Section of vault support and foundation detail: a) hollow brick (28x14x4 cm), b) thin-tile (28x14x1.2 cm), c) Portland cement mortar, d) gypsum, e) high strength fiber-reinforced mortar, f) membrane of polyurea, g) nodular drainage layer, h) geotextile, i) gravel, j) drainpipe k) mortar rendering, l) reinforced concrete slab, m) plastic sheet, and n) gravel.

The first layer of a thin-tile vault is the most difficult one to be built. Experience and ability with the trowel is needed to handle the fast-setting mortar and place the bricks in their desired position, without the help of a formwork as reference. Additionally, the type of brick used can also help or complicate the mason's task. Traditionally, thin tiles (1.5-2 cm thick) are used as the lightness of the units is one of the requirements to be able to build the vault "in space", with bricks momentarily cantilevering until stable sections are finished. However, a thicker brick edge of the brick would be easier to use, as it has more surface to adhere. On the contrary, a nice finish is more difficult to be achieved with thicker tiles in areas of high negative curvature, resulting in bigger joints, for mainly esthetical reasons particularly unfavorable on the intrados.

Choosing the right brick is thus a task to be undertaken cautiously. In this case, due to the fact that the masons were being newly introduced to this technique, a hollow brick with a thickness of 4 cm was used, thus combining a light weight unit with a large contact area. The same brick was used for the second and third layers, except for parts of the vault where that thickness was not needed -a thin tile (1.2 cm thick) was used for the third layer in these areas (Figure 2).

Despite the difficulties related to the learning period of the masons, and the limited time and budget, the works progressed satisfactorily thanks to the efforts of the entire team, the inventiveness of some of the Antioquian workers (Figure **3**.a) and the motivation of the student volunteers (Figure **3**.b), which, in addition, created a unique working environment.

Figure 3: a) One of the worker's improvised handmade tools, and b) student volunteers assisting with the construction (© Sergio González).

3. Design

The design sought to integrate the vault in its surrounding. In the context of the Park "Juanes de la Paz", a green roof as a natural continuation of the park was the result. Underneath the vault, the paved path widens to create a covered space, which shows some features of the traditional technique, unexpected and largely unknown to most passersby, such as a 9m-span unreinforced masonry arch, holes in the shell and an unusual formal expressivity to create the link between the green area and the interior through a twisted central support.

3.1. Form-finding method

Illustrated in Figure 4, the design of the vault was realized with the funicular form-finding software RhinoVAULT (Rippmann *et al*. [8]).

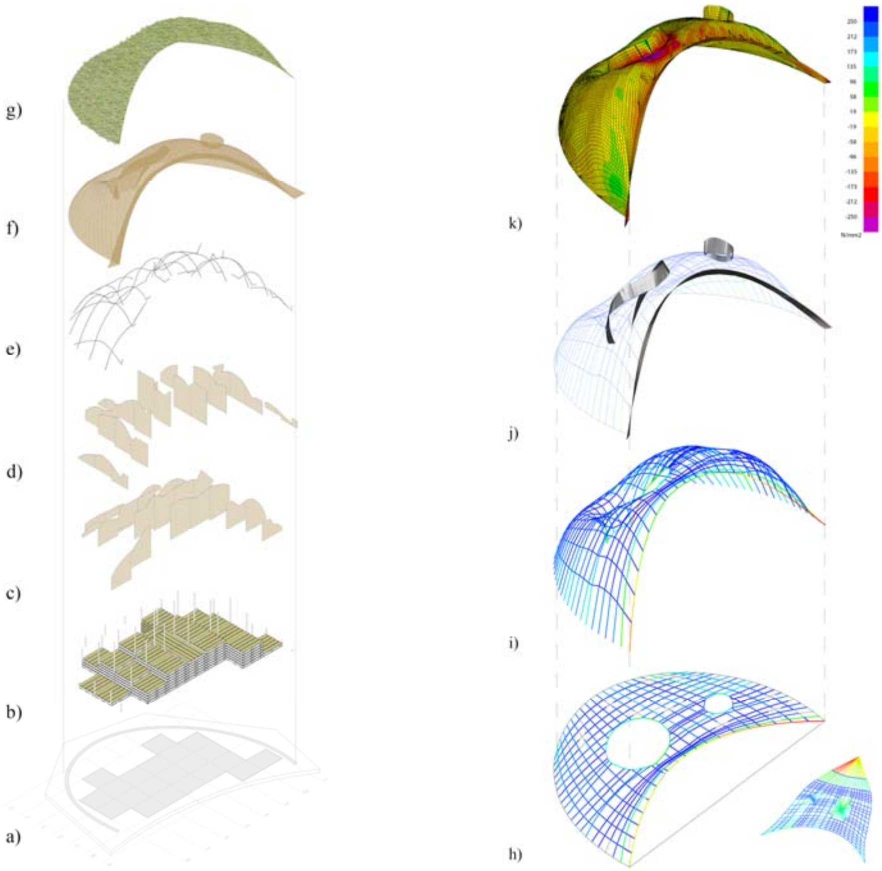

Figure 4: Exploded view of construction sequences, digital design process and structural analysis, including: a) concrete slab, b) pallets and wooden studs, c) and d) cardboard sections, e) spatial mesh of steel bars, f) thin-tile vault, g) green roof, h) form and force diagrams, i) thrust network, j) addition of "fins", k) FE analysis.

4. Structural Analysis

In ordinary masonry shells, compressive stresses typically remain low (tensile stresses due to asymmetric or possible punctual loading are usually more worrisome). In this case, as parts of the shell are covered with earth, a big amount of distributed dead load is applied. As an advantage, possible tensile stresses due to punctual loads become smaller, but as a complication, the compressive stresses may then also become important. Therefore, it had to be assured that these can be supported by the masonry.

In the exceptional spots, where the topography of the park and the conditions of the surroundings did not assure an equal distribution of the earth on the vault, the thickness of the shell has been calculated according to this high asymmetric loading, which could vary over time. The structural analysis has given the number of layers of brick needed to resist the stresses in these extreme cases.

4.1. Material properties

The material properties for the structural analysis using the finite element method were taken from the first author's Master Thesis (López López [5]). These properties, listed in **Figure 5**, are based on experimental tests on thin-tile vaults and specimens using the same materials and layer composition.

Young's modulus	Poisson ratio	Density	Tension	Compression
E [N/mm²]	*ν* [-]	*ρ* [kg/m³]	*ft* [N/mm²]	*fc* [N/mm²]
3200	0.15	1219.4	0.24	5.90

Figure 5: Material properties for the tile masonry considered for the FEM macro model

4.2. Loads

Dead, live and wind loads, as well as the self-weight of the structure were taken into account. The dead load considered for the green roof system was 2 KN/m^2. Although the roof is not meant to be accessible (ivy was planted instead of grass to discourage people these parts), a live load of 2 KN/m^2 was nonetheless applied considering the easy accessibility to the roof.

Taking into account the little overall height of the vault and its important weight (self-weight and dead loads), wind loads are not expected to produce a substantial alteration on the vault's state of the stresses. Nevertheless, a wind load of 1 KN/m^2 was considered.

Combinations of these loads were applied with the safety factors of 1.35 for dead loads and 1.5 for live loads.

4.2.1. Special load cases

The fact that the shell is semi-buried, adds a special load case applied in the parts where the vault is covered with earth. Additional horizontal pressure had to be taken into account. A density of a saturated earth of 20 KN/m^3 was applied.

The vault is placed on top of the stands of two soccer fields. The possibility that a group of people could climb onto the vault to watch a game from there had therefore to be considered. Regarding this hypothetical, but not unlikely situation, different load cases were created, each of them with nine punctual loads of 1KN scattered over the vault. Particularly, critical point loads along the open/unsupported edge were investigated.

4.3. Results

The compressive stresses in the structural analysis did not surpass 0.5 N/mm^2 -less than 10% of the compressive strength of the brick/mortar – with the most unfavorable load combinations and three layers of bricks (Figure 6.a). In the case of two layers, the maximum compressive stress, for the same loading cases, were less than 1.0 N/mm^2, still far below the compressive yield strength of 5.9 N/mm^2 (Figure 6.b). Therefore, as in regular thin-tile vaulted masonry structures, even with the large distributed loads from the green roof, tensile stresses due to asymmetric and/or punctual loads were the main factor deciding the vault's thickness.

Tensile stresses for a vault with two layers of brick and the most unfavorable load combination reach 0.7 N/mm^2, almost three times the tensile strength of the material. A third layer of bricks reduces the tensile stresses to less than 0.24 N/mm^2, which is the tensile yield strength of the material. Regarding the structural behavior of the vault and the appearance of tensile stresses, two different thicknesses of the vault were considered: 15 cm (three layers of hollow bricks + last rendering made of mortar) for the 1m-wide arch containing the main opening, spanning 9 meters; and 12 cm (two layers of hollow bricks + one layer of thin-tiles + last rendering) for the rest of the vault.

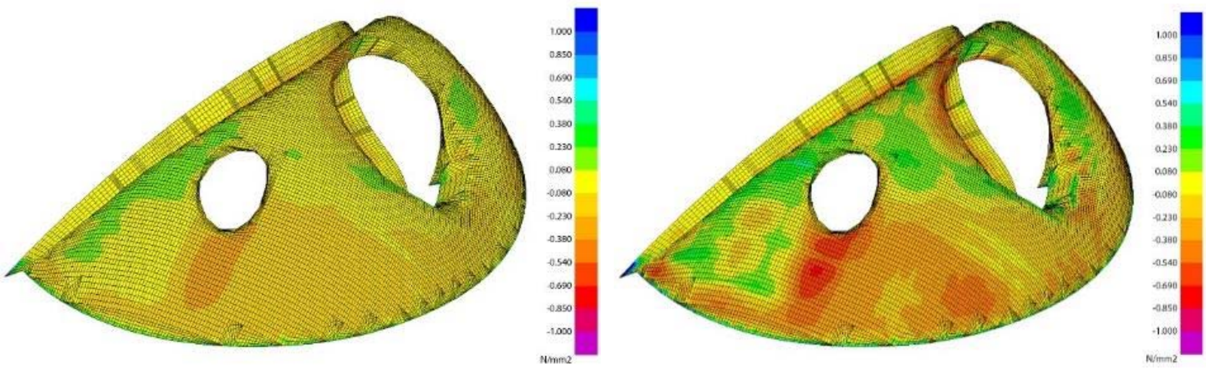

Figure 6: Stresses for the most unfavorable load combination for a) three layers of bricks, and b) two layers of bricks.

5. Construction

The vault was built using the traditional technique of thin-tile vaulting. However, the formal complexity of the vault required special attention to the falsework, which served as guide for the workers, but also supported the weight of the bricks until stable sections were reached.

The green roof is another particular and distinctive feature. To retain the green roof's earth in steeper areas, the compression-only shape is provided with edge elements that give the vault a very different appearance.

5.1. Falsework

A system of pallets, wooden studs, cardboard sections and steel reinforcement bars was employed to construct the falsework.

The pallets furthermore provided the workers a stepped working platform to easily reach all parts of the vault. Wooden studs were nailed to the pallets to indicate the precise height of the vault at specific points. These studs also provided a frame in between which the cardboard panels, cut in advance, could be attached. These cardboard sections showed the curves defining the vault surface (Figure 7.a). Following these, steel bars were bent and tied to each other to create the spatial mesh that would serve as falsework to build the vault onto (Figure 7.b). A continuous falsework is not needed, but, nevertheless, the denser the mesh is, the easier for the workers to achieve the precise shape of the vault design.


Figure 7: a) Construction of the falsework with cardboard sections and the studs as guides, rebars were bent in place; and b) the finished falsework (© Sergio González).

5.2. Green roof

The green roof consists of three layers of waterproofing and drainage materials, on top of which sacks with earth were placed. Plants were then seeded in these earth bags by making holes in the sacks.

Figure 8: Close-up of the layers of the green roof.

The entire vault was rendered with a high-strength, fiber-reinforced mortar in order to easily apply the waterproofing painting, but also to add stiffness to the shell. The waterproofing consists of a membrane of polyurea applied with brush and roller. On top of that, a nodular drainage layer and a geotextile were installed. Sacks made of geotextile were filled with earth and placed on top of these layers. Retaining elements were installed to allow arranging the sacks all over the surface of the vault, including the parts with steep slopes, without them sliding. These elements can be found all over the vault, but also along its edges in a more prominent way, giving a special feature to the vault (Figure 9).

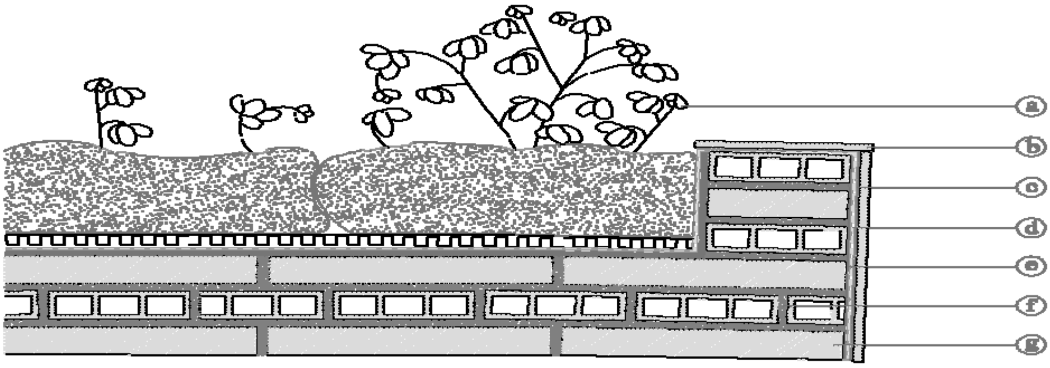

Figure 9: Detailed section of the edges: a) plants, b) thin-tile, c) mortar rendering, d) membrane of polyurea, e) high-strength fiber-reinforced mortar, f) Portland cement mortar, g) hollow brick (28x14x4 cm)

A good connection between the vaulted surface and the retaining edge elements was sought. Therefore, the layout of the bricks forming these "fins" shows bricks interlocking both elements and others sticking out of the "fin" to have as much surface as possible attached to the vault's surface (Figure 10).

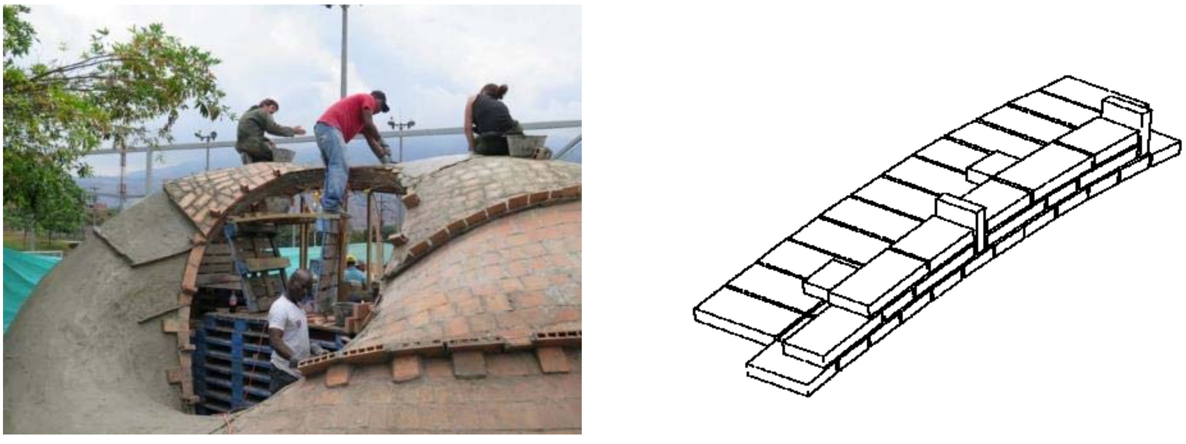

Figure 10: a) The retaining "fins" can be noticed, and b) layout of bricks forming the "fins".

6. Discussion

With this project, it has been demonstrated again that thin-tile vaulting can easily be exported to places where the materials are available. The geometries traditionally built with this technique were simple and easy to be constructed. However, the complexity of a free-form shell, like the one presented in this paper, poses challenges for the construction process and requires time for unexperienced workers to learn the technique.

The density and stiffness of the mesh making up the falsework are two factors to be taken into account when facing this kind of construction with unexperienced masons. A denser mesh will help them to obtain a more accurate shape, while a stiffer falsework will resist accidental blows or workers leaning on, which can both cause a deformation of the engineered reference surface or even cracks in already built masonry.

Figure 11: Fotos of the finished construction. © Sergio González

Acknowledgements

The authors would like to thank UN-Habitat, especially Petra Heusser and Zeltia Blanco, not only for choosing us to sign on this project, but also for their support and efforts during the entire process.

The work was supported by Ayuntamiento de Medellín, Ajuntament de Barcelona, SIKA, Groncol, Alfarera Pueblo Viejo, Smurfit Kappa and BASF.

The authors would also like to thank all the workers and the assistants Isabel Cristina Muriel Alzate, Juan José Ochoa Tejada, Juan Luis Zapata Vargas and Senn Carolina Alzate Gaviria (Universidad Nacional de Colombia), Katherine Prater and Mallory Taub (ARUP) and Ana Gatoo (University of Cambridge).

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