



## “Brick-topia”, the thin-tile vaulted pavilion



David López López<sup>a,\*</sup>, Marta Domènech Rodríguez<sup>b,1</sup>, Mariana Palumbo Fernández<sup>c,2</sup>

<sup>a</sup> Block Research Group, ETH Zurich, Stefano-Francini-Platz 5, CH-8093 Zurich, Switzerland

<sup>b</sup> Design Department, School of Architecture of Barcelona, UPC, Av. Diagonal 649, 08028 Barcelona, Spain

<sup>c</sup> GICITED, School of Building Technology of Barcelona, UPC, Av. Doctor Marañón 44, 08028 Barcelona, Spain

### ARTICLE INFO

#### Article history:

Available online 23 September 2014

#### Keywords:

Brick-topia  
Formwork  
Free-form  
Catalan/thin-tile vault  
Structural analysis  
Construction

### ABSTRACT

The project “Brick-topia” was based on a combination of the latest structural analysis and form-finding computational tools with traditional, cheap and effective construction techniques. It is the result of innovation to fight against budget and time. The initial budget was 3000 euros and only seven weeks was the time to look for sponsors, design the pavilion, plan the construction phases and build it.

The whole process of designing, decision on the materials, structural analysis and construction is presented in the paper, including exploration on new form-finding methods to redesign a project in situ and research on a new formwork system using scaffolding, cardboard, wire and steel rods and having a cutter as main tool.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

### Introduction

The international collective of architects Map13 ([www.map13bcn.com](http://www.map13bcn.com)), which the authors cofounded, won the contest to build a pavilion at the International Festival of Architecture Eme3, to be held from the 27th to 30th of June 2013 in Barcelona, Spain. The building was a vaulted unreinforced masonry structure made with the traditional technique of thin-tile vaulting (also known as “Catalan vault”). It reached a maximum height of 4 m, had spans between 5 and 7 m and the shell had a surface of 150 m<sup>2</sup> (Fig. 1).

“Catalan vaults” are masonry structures made with bricks and binder. The bricks are placed flat setting 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” (without a continuous formwork, Fig. 2) using gypsum or fast setting cement. The aim of using these binders for the first layer is the quick adhesion achieved so that the bricks get attached within seconds to the edge walls or to the previous arcs or stable sections already finished, cantilevering for some time and avoiding the necessity of centering [1]. The second and subsequent layers can be set with lime or Portland cement mortar.

The “Brick-topia” pavilion takes as reference and inspiration the prototype built by the Block Research Group at the ETH in Zürich [2], but “Brick-topia” is the first free-form “Catalan vault” at such a scale. Increasing the size, opening it to the public and the constraints of time and budget, meant necessary innovation in the construction process, as well as meticulous structural analysis. These aspects are presented in this paper, together with the materials used and the form-finding method.

\* Corresponding author. Tel.: +41 786 364 414.

E-mail addresses: [lopez@arch.ethz.ch](mailto:lopez@arch.ethz.ch) (D. López López), [marta.domenech@upc.edu](mailto:marta.domenech@upc.edu) (M. Domènech Rodríguez), [mariana.palumbo@upc.edu](mailto:mariana.palumbo@upc.edu) (M. Palumbo Fernández).

<sup>1</sup> Tel.: +34 657 324 743.

<sup>2</sup> Tel.: +34 669 580 593.

## Materials

There were three main elements composing the building: the concrete slab, the bricks and the binders (Fig. 3).

### Concrete slab

As no perforations on the ground were permitted, superficial foundations had to be implemented. The slab was made of reinforced concrete and served as foundation for the entire structure. The surface of the concrete slab was 285 m<sup>2</sup> and 120 mm thick. The reinforcement consisted of 8 mm diameter steel bars in both directions every 150 mm. Steel reinforcement was placed where needed depending on the horizontal thrusts in each support.

### Bricks

Selecting the right bricks is essential in this kind of construction, especially for the first layer. The first layer is built “in space” using light bricks, which will be cantilevering for some moments depending only on the fast-setting mortar capacity to hold it from its edges. Traditionally thin bricks approximately 15 mm thick are used, but also hollow bricks of 40 mm are suitable, as they are also light and have more surface at the edge, improving the adherence during the construction process.

The bricks used in the project for the first layer were traditional handmade bricks, 280 × 140 × 15 mm. Their weights may vary, but it was approximately 1 kg per piece. The quality of these thin-tiles in terms of spatial warmth and aesthetics by color variety and finishing, is hardly achieved by industrialized bricks.

The second layer was made with hollow industrialized bricks, 280 × 140 × 40 mm, still light (1.5 kg per piece) to prevent an excess of weight on the first layer. The price of these pieces was also a reason for its election as the budget was tight and the sponsorship of the companies offering bricks could not cover every layer.

The third and final layer was not applied to the whole construction. It was only built over the biggest vault, with the rest of the building only two layers thick (a thickness of 65 mm in total). Solid bricks were used, with dimensions 280 × 140 × 43 mm, 3 kg weight each and a handmade texture. The weight of the third layer, instead of being a handicap, helps reaching the stability against possible destabilizing punctual loads. Adding a uniformly distributed load does not harm the structure, as it is designed to be a compression-only structure and the stresses in masonry structures are normally low in comparison with the compressive strength of the material.

Approximately 4100 bricks were used for each of the first two layers and 1400 for the third one.

### Binders

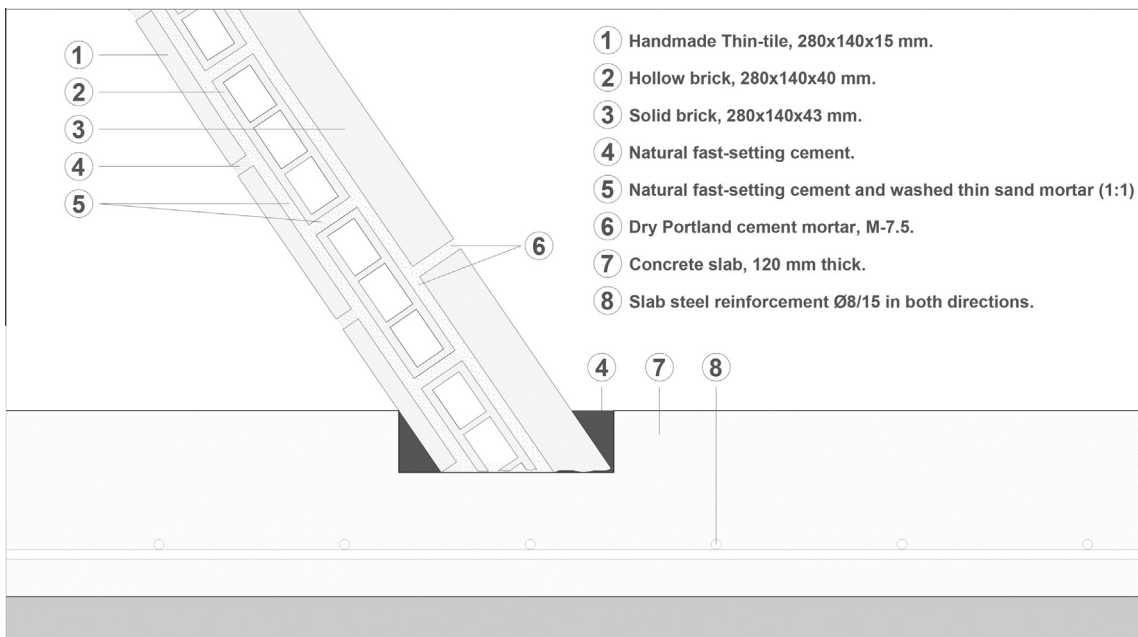
The two binders that can be used to build the first layer of a “Catalan vault” are plaster of Paris (gypsum) or fast-setting cement. In this case, a “natural rapid cement” was chosen because of its resistance to exterior conditions, its strength and the quickness of this strength to be achieved. Due to the weather conditions with temperatures over 30 °C at the worksite, ice cubes were used to obtain cold water to make the mix and slow down the setting process. Retardant powder was also added to the water (25,000 mm<sup>3</sup> per 8 liters of water).



Fig. 1. General view of the project. © Manuel de Lózar and Paula López Barba.



**Fig. 2.** Building Brick-topia's first layer of bricks: (a) applying fast-setting cement and placing the brick, (b) cleaning the joint. © Manuel de Lózar and Paula López Barba.



**Fig. 3.** Detail of the support.

For the first layer only rapid cement was used as binder. For the second layer a mix of rapid cement and washed thin sand (1:1) was applied. This mix is more difficult to work with than Portland cement mortar as the rapidity of setting makes it more unworkable, especially for a second layer, in which more binder is used than in the first one because of the necessity to have also binding material between layers. However, as mentioned above, this option was chosen because of the quickness in achieving its strength and the proximity to the inauguration of the building.

For the third layer grey dry Portland cement mortar was used. An already mixed mortar was selected to speed up the production.

The thickness of the joints vary between 5 mm and 10 mm, with the joints between layers slightly wider than the joints between bricks in the same layer.

### Form-finding method

The shape of the pavilion is the result of a thorough design process using the software RhinoVault. This tool is a plug-in of Rhinoceros developed at the Block Research Group in the Institute of Technology in Architecture at the ETH in Zürich. It



Fig. 4. Panoramic view showing some features of the design.

allows the design of compression-only vaulted structures with a high formal complexity. The theoretical basis of the software is Thrust Network Analysis (TNA), a method to generate “possible funicular solutions under gravitational loading within a defined envelope” [3].

*“Using reciprocal diagrams, it provides an intuitive, fast method, adopting the same advantages of techniques such as Graphic Statics, but offering a viable extension to fully three-dimensional problems. Our goal is to share key aspects of our research in a comprehensible and transparent setup to let you not only create beautiful shapes but also to give you an understanding of the underlying structural principles.” [4,5]*

The design had two principal goals: (1) fulfil the requirements specified by the client making a functional pavilion for the site with a clear intention when defining the openings and closed spaces, (2) explore the possibilities of the construction technique providing the building with different features that would take the structure to the limit (Fig. 4).

Some of the features that were incorporated in the design are inclined thin supports, arches that cannot be inscribed in a plane, a twisting support where arches in perpendicular directions land, different heights of the vaults, different degrees of curvature and a big hole in the shell.

### Structural analysis

As discussed earlier, the form-finding method using RhinoVault guarantees a shape working in compression when it is only subjected to self-weight loads. However, according to the Spanish code, the admissibility of possible different live loads needs to be verified. The building should be able to resist the applicable wind, snow and maintenance loads specified in the code with their corresponding safety factors. Maintenance distributed load is  $1 \text{ kN/m}^2$ , the snow load applicable for the city of Barcelona is  $0.4 \text{ kN/m}^2$ . The wind load varied between  $1$  and  $1.4 \text{ kN/m}^2$  depending on the direction and taking into account the wind’s dynamic pressure, the exposition of the specific points of the building depending on its height and location and the wind coefficient depending on the shape and orientation of the specific surface. The safety factors are 1.35 for dead loads and 1.5 for live loads [6].

To perform the structural analysis, the Finite Element Method was used [7]. A macromodel and the corresponding loads and combinations were defined. For the maintenance load, not only a distributed load was applied, but also, according to the code, punctual loads of  $1 \text{ kN}$  were placed in several spots attempting to find the most unfavorable situation.

The material properties applied to the macromodel (Table 1) were taken from the master thesis of one of the authors, David López López: *Structural Analysis of Tile Vaults: Methods and Variables*, within the MSc in Structural Analysis of Historical Constructions (UPC and UMINHO). In that thesis, the tests on built vaults and specimens, together with the FE non-linear

**Table 1**  
Material properties for the FEM macromodel.

	Young’s modulus $E$ $\text{N/mm}^2$	Poisson ratio $\nu$ –	Density $\rho$ $\text{kg/m}^3$	Tension $f_t$ $\text{N/mm}^2$	Compression $f_c$ $\text{N/mm}^2$
Masonry	3200	0.15	1219.4	0.24	5.90

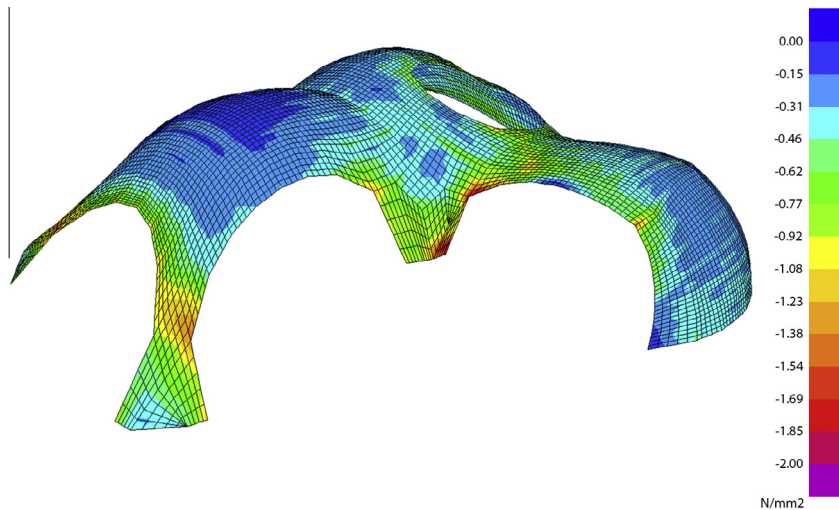


Fig. 5. Compressive stresses for the most unfavorable load combination.

analysis and the comparison of the results allowed the compilation of the material properties of that specific type of masonry.

No experimental tests could be carried out on specimens with the exact material composition used in this project. Bricks and binder composing the masonry in “Brick-topia” were solid bricks (first and third layers) and fast-setting cement, while hollow bricks for every layer and gypsum were used in the mentioned thesis’ tests. The masonry in “Brick-topia” would have a better behavior knowing that the fast setting cement had a higher strength guaranteed by the producer and based on two assumptions: that solid bricks have a higher strength and that a higher density of the bricks, i.e. more self-weight, would not be harmful for the structure providing it is a compression-only shape. Moreover, as long as the compressive strength ( $f_c$ ) of the masonry is not reached – which rarely happens in this kind of structures – the addition of self-weight would be positive as it helps to stabilize the structure against possible punctual or asymmetrical loading. Thus, assuming for this project the material properties of López’s dissertation would never be counterproductive in terms of structural safety, on the contrary, it gives an additional safety factor to the structure.

As mentioned above, masonry structures have usually low compressive stresses comparing to the compressive strength of the material. The analysis performed resulted in the same conclusion: while the adopted compressive strength was  $5.9 \text{ N/mm}^2$ , compressive stresses did not even reach  $2 \text{ N/mm}^2$  (Fig. 5). Tensile stresses became then the key factor of the analysis and the justification of the vault’s thickness.

The application of the different load combinations to the model resulted in the development of tensile stresses. The thickness of the vault was then increased in the needed places until the tensile stress was admissible.

The most unfavorable situation was caused by punctual loads at the two inclined supports, almost independently of the wind and snow load cases. The analysis applying this load combination with a thickness of  $65 \text{ mm}$  – two layers of bricks – in the whole vault showed non-admissible tensile stresses at these supports reaching  $0.48 \text{ N/mm}^2$ . Increasing the thickness to  $118 \text{ mm}$  – three layers of bricks – was enough to reach acceptable values (maximum tensile stresses reported were  $0.13 \text{ N/mm}^2$ ). Running the analysis with the different load combinations and changing the vault’s thickness according to the results, resulted in a pavilion with two different thicknesses. Approximately half of the structure has two layers whereas the other half has three.

## Construction

Apart from the intrinsic limitations of the material, two parameters were the main constraints during construction: time and budget. Fast and economical construction systems needed to be implemented in order to achieve the proposed goals.

### Falsework

Formwork is usually one of the most challenging parts when building a shell; not only because it means a provisional structure to build the final one, but also because it is normally expensive and time-consuming. This fact puts architects and engineers to the test of being able to come up with better solutions in terms of costs, schedule, sustainability, ease of implementation, versatility, etc.

The combination between the computational tool RhinoVault and the use of the Catalan vault as construction technique, already put into practice by the Block Research Group [2], opened a new horizon in the designing of free-form shells and the

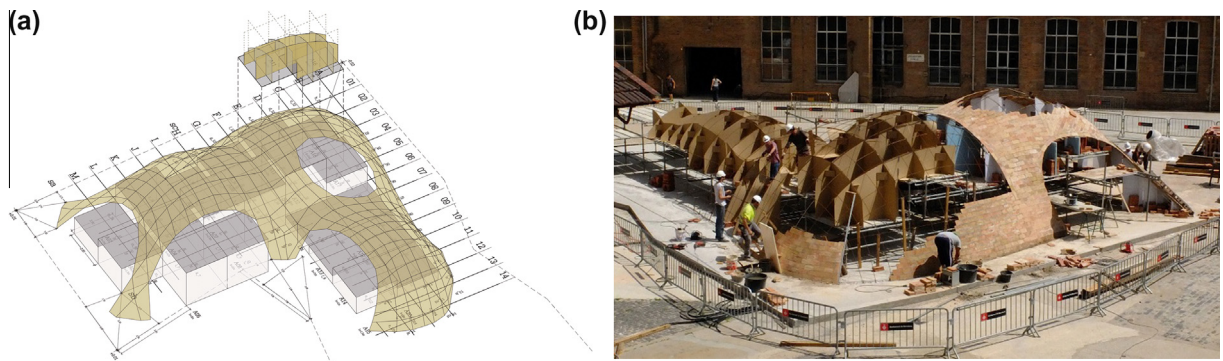


Fig. 6. Formwork scheme: (a) axonometry, (b) construction (© Manuel de Lózar and Paula López Barba).

ease of their implementation. However, a more complex falsework is needed than in conventional “Catalan vaults”. Traditionally, no load bearing falsework is needed, as the geometry of the vault is normally reached by building stable portions of the structure during the construction process. Falsework used in free-form Catalan vaults needs to have load bearing capacity to support the self-weight of parts of the structure until stable arches or portions of the structure are built. However, as the self-weight of thin-tile vaults is low in comparison to other masonry structures, the falsework does not have to support high stresses.

The solution adopted had three main elements or materials: scaffolding, cardboard and steel rods. The final shape and load bearing capacity of the falsework is given by a grid of bent steel rods.

The scaffolding was composed by 2 m by 2 m modules at different levels depending on the height of the vault at the specific area. Sections every meter were extracted from the model in two perpendicular directions. Cardboard panels, 2 m by 2 m, were cut on site following the shape of the sections. Each module of the scaffolding served as the base for a system of four stable intersecting cardboard panels (Fig. 6). When the whole shape had been defined by the cardboard panels, 6-m-long steel rods were placed on the top edges of the cardboard shaping the vault. First,  $\varnothing 10$  mm steel rods were placed in one direction and secondly,  $\varnothing 8$  mm rods were disposed in the perpendicular direction. They were tied together with wire where they intersect. Additional  $\varnothing 12$  mm steel rods are placed on the net shaping the main arches and providing an edge where the bricks can rest while building the arches. Depending on the accessibility and taking into account the need of the builders to work through the falsework, some supplementary steel rods are situated in between the main ones making the grid denser in some locations: 0.5 m by 0.5 m. Once the steel bar grid is built, the cardboard can be removed and the builders can work standing on the scaffolding (Fig. 7).

The expected error between the designed shell and the final shape of the falsework, due to the manual process of building, does not affect the stability of the vault. Even in very slender vaults, thrust lines are normally inscribed within the thickness of the vault. If they would eventually surpass those limits, the little, but existing, tensile capacity of the material would help to avoid failure. Besides, thanks to the net of steel bars, a continuous vaulted shape is always achieved and there is little



Fig. 7. Grid of bent steel rods. © Manuel de Lózar and Paula López Barba.

possibility to have pointed spots or sharp edges which could be the cause of tensile stresses on the vault. Furthermore, if those cases would eventually happen, they would be very easily localized during the setting of the steel bars' net and they could be fixed before the brick construction starts.

Implementing this fast system allowed the masons a quick start with the first layer of bricks. Besides, the usage of economical materials and simple tools such as rulers and cutters to measure and cut the cardboard reduced the budget significantly.

#### *Redesigning in situ*

The dimensions of the planned vault had to be reduced at some point of the construction process due to schedule problems. A quick redesign of one of the sides of the vault was needed. The knowledge about structural behavior of Catalan vaults and the previous experience in constructing them, allowed the authors to change the design of the vault successfully on site. A new simple form-finding method was explored: only the 6-m-long steel rods carefully bent were enough to redesign a new shape in which the authors could predict on site an appropriate force flow to the supports to make the structure work only in compression. After the new form was designed and fixed with a grid of steel bars, it was translated to a digital model and validated by a new structural analysis with FEM.

The new solution configured a concave and intimate space inside the vault while presenting a new formal feature due to the high degree of curvature of the new shape. Three other main reasons led to the solution adopted: (1) a double curvature shape was designed to increase its stability, (2) a continuous support was preferred to provide the maximum number of possible paths for the forces to reach the ground, (3) arches were not a good option because, even though they mean less bricks to be placed, they need more time to be built on account of the more difficult falsework, the instability during construction and the need to cut more tiles with a specific pattern.

#### *Decentering*

One of the most exciting and challenging moments of the construction of a conventional masonry structure is the removal of the formwork. At that moment the structure begins to work by itself and it is the first critical proof to know if it has been well built and designed. Many different strategies have been proposed through history to avoid cracking, unexpected settlements and/or failure. Many of them recommend a careful and simultaneous decentering of the whole structure. Each masonry construction should be deeply studied as decentering can be a dangerous process.

The formwork removal in the case of "Brick-topia" was indeed exciting and a highlight of the construction process because it was the moment when the structure could be observed from the inside without the scaffolding and the whole space could be experienced; however, it was not dangerous at all, nor as critical as it could be thought.

The formwork in "Brick-topia" could only support the self-weight of the first layer of bricks and some occasional loads that the workers may accidentally apply. Therefore, the vault itself already started to work when the second layer was being built and tools, construction material and workers were standing on the two-layered vault to continue the construction process. If the formwork is not carrying any load once the vault is finished, decentering becomes then a simple and non-dangerous task.

The formwork of the highest part of the vault was finally removed two days before the works finished in the rest of the vault in order to show at the festival of architecture Eme3 some steps of the whole construction process (the building of the second and third layers in different parts of the vault, the decentering and the finished aspect). The decentering consisted of cutting the wire that connected the steel bars to each other and by detaching them from the scaffolding and slab. Special care



**Fig. 8.** Opening of the pavilion. © Manuel de Lózar and Paula López Barba.

had to be taken when releasing a steel rod from the grid, as it could hit the workers when it suddenly was free to recover its initial straight shape.

## Conclusions

One of the most remarkable features of this project was the success of the formwork system. The initial idea came from the scheme developed for the prototype in the ETH Zurich [2], however, it was adapted to the new size and constraints and the final formwork system became very different. Although it worked well in this project, some improvements could be made to avoid movements on the net of steel rods that could cause cracking, such as more points fixing the spatial net to the scaffolding, which would have helped to reach a higher stiffness on the net. A big improvement could also be done providing the formwork with a thicker edge at the arches so that the bricks would lay on it and would not slide while the arch is not yet completed.

The combination between a graphic statics based form-finding method (TNA [3] and RhinoVault [5]) and FEM as further structural analysis in 3D was also one of the key aspects of the process. They were complementary, thus the final result could not have been achieved using only one of these tools.

More research needs to be done in order to optimize timing and construction processes. However, the construction of this pavilion already means a significant step forward in shell construction and the demonstration of the possibility to build large, suggestive, habitable and safe free-form vaulted spaces with an inexpensive, efficient and sustainable technique: thin-tile vaulting [8] (Fig. 8).

## Acknowledgments

“Brick-topia” was possible thanks to Josep Brazo Ramírez, who believed in it from the very beginning, got involved in it and taught us so much about “Catalan vault” construction.

The authors would like to thank as well Paula López Barba, part of the execution team, for her help and support.

The work was supported by Sapic, Cots i Claret, Closa, Calaf, Urcotex, Cementos Collet, Bòvila Artesana Durán, Ceràmiques Piera, IAAC, Cemex, Presolera, Alsina, Nudec, GTC, Alco, Rubí, COAC and ETSAB.

The authors would also like to thank all the volunteers and workers at “Brick-topia” and the International Festival of Architecture Eme3.

## References

- [1] Huerta S. In: Instituto Juan de Herrera, editor. *La Mecánica de las bóvedas tabicadas en su contexto Histórico: la aportación de los guastavino*. Madrid: Las bóvedas de Guastavino en América; 2001. p. 87–112.
- [2] Davis L, Rippmann M, Pawlofsky T, Block P. Innovative funicular tile vaulting; a prototype in Switzerland. *Struct Eng* 2012;90(11):46–56.
- [3] Block P. Thrust network analysis: Exploring three-dimensional equilibrium [Ph.D. dissertation]. Cambridge, USA: Massachusetts Institute of Technology; 2009.
- [4] Rippmann M, Lachauer L, Block P, Block Research Group, ETH Zürich. <<http://block.arch.ethz.ch/brg/tools/rhinovault>>; 25th November 2013.
- [5] Rippmann M, Lachauer L, Block P. Interactive vault design. *Int J Space Struct* 2012;27(4):219–30.
- [6] Código Técnico de la Edificación, Documento Básico, Seguridad Estructural, Acciones en la Edificación (CTE DB SE-AE), Spain; 2009
- [7] López López D, Domènech Rodríguez M, Palumbo Fernández M. Using a construction technique to understand it: thin-tile vaulting. In: Peña F, Chávez M, editors. SAHC2014 – 9th international conference on structural analysis of historical constructions, Mexico City, Mexico; 2014.
- [8] López López D, Domènech Rodríguez M. Tile vaulting as an alternative. 38 International Congress of the “International Association for housing Science” (IAHS), 2012.