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USING A CONSTRUCTION TECHNIQUE TO UNDERSTAND IT: THIN-TILE VAULTING

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Abstract. *"The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage"* [1].

The Venice Charter showed a new understanding of historical constructions' conservation. In particular, the way that it is defined in the first two articles widen the field to give a prominent place to the conservation of cultural values and traditional techniques. Thirty years later, in 1994, the Nara Document on Authenticity defined conservation attaching great importance to the *"efforts designed to understand cultural heritage"* [2].
This paper presents the result of research aiming to understand the material performance, construction processes and structural behavior of a traditional technique that has given countless examples of architectural heritage and can itself be considered as a cultural and heritage value to be preserved: thin-tile vaulting (or Catalan vaulting).
The final outcome of this research is a pavilion entirely built with the mentioned technique. The building exhibits the possibilities of the technique in terms of material expressiveness, formal appearance and structural behavior. The whole process of erecting the building meant necessary research from three perspectives: historical, analytical and experimental.
The processes of design, construction and structural analysis are presented in this communication giving a new perspective and broader understanding of the technique to give hints that could help in the conservation and restoration of existing specimens.

"…the essential contribution made by the consideration of authenticity in conservation practice is to clarify and illuminate the collective memory of humanity" [2].

1 INTRODUCTION

Although the preservation of heritage was being encouraged by many different ways -one could infer that researching on ancient building techniques could be one of them-, no chance was given to these techniques to be included in the definition of "cultural heritage" given at the UNESCO World Heritage Convention in 1972 [3]. Only monuments, groups of buildings and sites could be considered "cultural heritage". It has to be said that the aim of the text was not to define concepts or set recommendations concerning heritage preservation, but to establish "an effective system of collective protection of the cultural and natural heritage". However, the need to define specific concepts -without further comments or related definitions-, narrowed what had been a new understanding of architectural heritage since the Venice Charter (1964), eight years before.

The Venice Charter did not define a "historic monument" in a very different way, but it went deeply in the analysis and clarification of "the principles guiding the preservation and restoration of ancient buildings", which made a clearer and wider picture of the role of tradition, history, science and techniques in the fields of conservation and restoration. A monument was not only a piece of art, but also a historical evidence. Traditional techniques could be then considered an important feature of the monument as they were part of its history.

Thirty years later, the concept of authenticity appeared in the Nara Document of Authenticity (1994) as "the essential qualifying factor concerning values". The difficulty of the definition of the term and the awareness of the different cultural contexts set a scenario in which basing judgments of values and authenticity within fixed criteria was not possible. However, this subjectivity also left a door open to the inclusion of traditional or historical building techniques into the aspects to be preserved.

"*Depending on the nature of the cultural heritage, its cultural context, and its evolution through time, authenticity judgments may be linked to the worth of a great variety of sources of information. Aspects of the sources may include form and design, materials and substance, use and function, traditions and techniques, location and setting, and spirit and feeling, and other internal and external factors.*" [2].

1.1 Background

"Catalan vaults" or thin-tile 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" 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, avoiding the necessity of centering [4]. The second and subsequent layers can be set with lime or Portland cement mortar.

"Modern theory finds it difficult to explain and measure the phenomenon of its resistance, and the builders who showed their genius in understanding the vaults are dead and buried beneath the clay which they used to make the brick centuries ago" Eduardo Torroja [5].

Many architects and engineers have developed and used different structural theories to assess this kind of constructions. However, many of them were opposed or could not explain the

real behavior of the vaults. Even today the debate about the existence and the need of the tensile stresses to be considered is still an issue in every congress about the matter. The method to be used to analyze these vaults is also a matter of discussion, having great defenders of the limit analysis and giving no reliability to the Finite Elements Method and, on the other hand, arguments saying that this later method is also suitable and can provide important information about the structural behavior of masonry structures.

2 OBJECTIVE

The research that is partly presented in this paper is not only focused on giving solutions for the structural analysis of historical constructions containing thin-tile vaults, but it can also be valid to be consulted when facing a new project recovering this historical technique. In fact, these two aspects are inseparable in this research, as experimental constructions, tests and hands-on work with the technique are considered within this research the best ways to understand the material, construction process and structural behavior of the technique.

Furthermore, thin-tile vaulting is a traditional building technique from the western Mediterranean abandoned as an usual construction system, but able to be retrieved considering its qualities such as its low cost, formal versatility, load bearing capacity, sustainability and durability.

Nevertheless, special attention has been given to the substantial differences when facing a new project and the conservation of a historical construction. According to the ISCARSAH Recommendations (2001) [6], ancient structures need a different approach strategy, involving historical investigation, inspection, monitoring and structural modeling and analysis. Obviously, this scientific multidisciplinary approach is not needed when building a new structure. However, there are other not so self-evident differences that concern the way the structural analysis is performed or even the kind of analysis to carry out.

This research, according to what has been stated above, is addressed from three perspectives: historical, numerical and experimental. The most representative example of the latter is presented in this paper: the project Brick-topia (Figure 2). However, it is not the only effort by the authors to promote the thin-tile vaulted technique. The belief in the advantages of the technique [7] has resulted in many hands-on workshops where students and professionals could build “Catalan vaults” with their own hands (Figure 1).

Figure 1: workshops tutored by the authors teaching and promoting thin-tile vaulting.

3 BRICK-TOPIA

The international collective of architects Map13 (www.map13.net), which the authors co-founded, 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 called "Brick-topia" and was a vaulted unreinforced masonry structure entirely made with the traditional technique of thin-tile vaulting. It reached a maximum height of 4 meters, had spans between 5 and 7 meters and the shell had a surface of 150 m^2. The reference and inspiration of this pavilion can be found in the prototype built by the BLOCK Research Group at the Swiss Federal Institute of Technology in Zurich (ETH Zürich) [8].

Figure 2**:** General view of the project Brick-topia**.**

3.1 Brick-topia's structure

3.1.1. Form-finding method

The relation between shape and structure is obviously very important to build a logical or sincere building; however, it becomes essential when the construction material has any inevitable restriction, as it is the case of masonry structures. Therefore, the form-finding process becomes crucial to avoid, as much as possible, undesirable tensile stresses which masonry would not be able to resist.

The structure of Brick-topia was designed with the help of the software RhinoVault (Figure 3), which allows the creation of complex –or also simple- compression-only structures. This software was developed by Rippmann, Lachauer and Block (BLOCK Research Group) at the ETH Zürich. This software is based on Thrust Network Analysis (TNA), developed in the doctoral thesis of Prof. Dr. Philippe Block [9].

"*the resulting methods for the horizontal and vertical equilibrium can be implemented in a modern CAD environment, to create a form finding tool that provides intuitive control over the complex relation between form and forces of three-dimensional compression-only structures*" [10].

However, RhinoVault guarantees a shape working in compression when it is only subjected to its self-weight. 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 [11]. A structural analysis involving those load cases and combinations is thus needed.

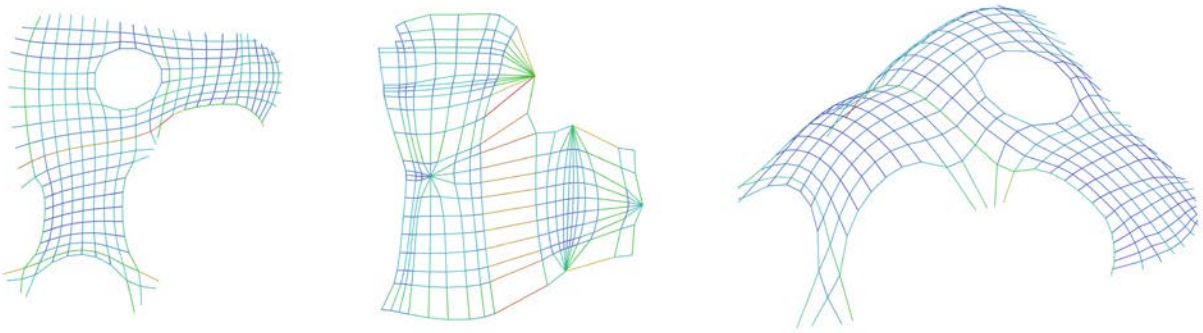

Figure 3: Form finding with RhinoVault. a) Form diagram, b) force diagram, c) thrust network.

3.1.2. Structural analysis

Material properties

The structural analysis of Brick-topia would not have been possible without the previous research done by the authors on the structural behavior of thin-tile vaults and the experimental tests carried out for the master thesis of David López López: *Structural Analysis of Tile Vaults: Methods and Variables,* within the Erasmus Mundus Advanced Masters in Structural Analysis of Historical Constructions (UPC and UMINHO). The reason is not only because of the knowledge acquired on the field, but also because the material properties for the analysis using the Finite Element Method (FEM) were collected from that work (Table 1).

The tests on built vaults and specimens, together with the FE non-linear analysis and the comparison of the results allowed the compilation of the material properties of that specific type of masonry. As tests to determine the tensile strength of the material were not possible to perform, the comparison of the experimental and the numerical results was imperative to adjust the model to be able to replicate the same behavior as the experiments and therefore obtain the missing material properties. The materials used to build the two-layered vaults and specimens were: hollow bricks, fast setting gypsum and mortar. The bricks were hollow bricks measuring 28cm x 14cm x 4cm.

Table 1: Material properties for the FEM macromodel.

	Young's modulus	Poisson ratio	Density	Tension		Compression	
	E	*v*	*ρ*	*ft*	*GfI*	*fc*	*Gfc*
	N/mm^2	-	kg/m^3	N/mm^2	N/mm	N/mm^2	N/mm
Masonry	3200	0.15	1219.4	0.24	0.14	5.90	9.44

The materials used in Brick-topia were not the same: three different kind of bricks for the different layers (thin, hollow and solid bricks), fast-setting cement and mortar. However, the

mentioned material properties could be used to perform the analysis of the pavilion taking for granted that 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 compression strength 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.

Finite Element Method

As mentioned above, the structural analysis of a new masonry building may be very different than the one of a heritage structure. The structural analysis regarding heritage structures is used for the phases of diagnosis, safety evaluation and design of intervention. The causes of cracking, crushing or other kind of damages should be understood and the ultimate capacity of the structure may be necessary to be known. A linear elastic analysis in this cases is not appropriate as it cannot take into account the limited tensile strength of the material, thus neither simulation of cracking or other phenomena nor safety evaluation is possible and only limited qualitative information can be expected from this kind of analysis [12].

A different strategy can be followed facing the analysis of a new structure. In this case, it is the decision of the architect/engineer to allow cracking or to perform a more or less conservative analysis. Linear elastic and geometrical analysis with FEM has been used regularly by technicians due to its availability and reduced computer costs and it may be used for the structural assessment of new masonry constructions. However, it should be carefully employed taking into account that the relationship between strains and stresses is linear with no strength limitation.

A linear analysis with FEM was used to assess Brick-topia's structure. A minimum thickness of 6.5 cm (two layers of brick) and the required load combinations were applied to the model. The thickness was increased in the areas where inadmissible tension stresses appeared. The result was two different thicknesses in the pavilion: 11.5 cm at the higher and bigger vault and 6.5 at the rest of the building (three and two layers of bricks respectively) [13].

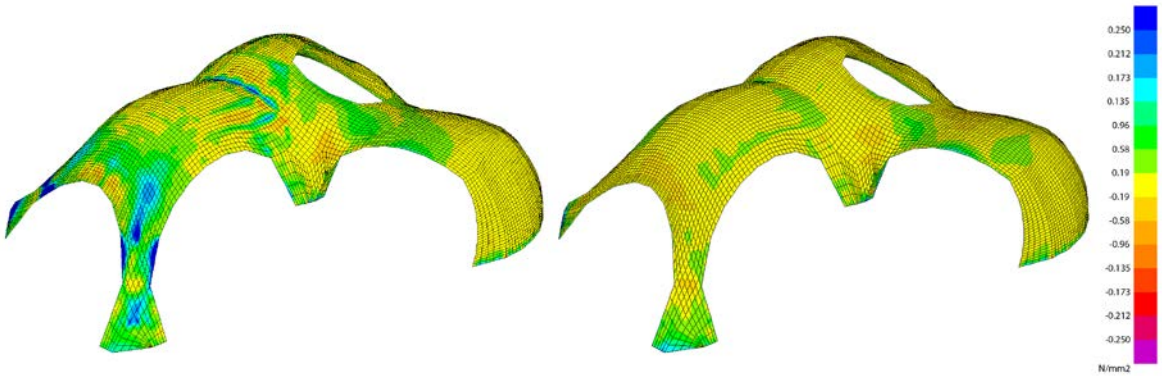

Figure 4: Maximum stresses for the model with 1kN punctual loads at the two longer supports –most unfavorable load combination- for a) thickness 6.5 cm, and b) thicknesses 6.5 and 11.5 cm.

3.2 Brick-topia's construction.

Traditionally, "Catalan vaults" do not need a load bearing formwork, as the geometry of the vault is normally reached by building stable portions of the structure during the construction process. However, the formal complexity of the pavilion requires the use of a falsework, both to serve as guide to achieve the exact shape and to support the weight of the bricks until stable sections are reached.

A system of scaffolding, cardboard sections and steel reinforcement bars was employed to construct the falsework (Figure 5) [13].

Figure 5: a) Construction of the falsework with cardboard sections and rebars; and b) building the vault on the falsework. © Manuel de Lózar and Paula López Barba.

4 CONCLUSIONS

The current understanding of preservation of ancient architecture encourages the research on traditional techniques used in historical constructions. An approach from different perspectives is needed in order to be fully aware of every aspect of the technique to be studied. An experimental approach is thus fundamental. In addition, in this specific case, experimentation with thin-tile vaulting is also justified as it is a technique which is subject to be recovered due to its qualities of sustainability, low-cost, durability and versatility.

Figure 6: Interior of the pavilion.

Although the materials and technique may be the same, the approach to the structural analysis of an existing historical construction and a new building can be different. Whereas a multidisciplinary approach and a non-linear structural analysis is usually recommended in existing structures, in the case of new buildings, the architect/engineer has more freedom to decide whether a linear analysis could be enough provided that the limitations of this kind of analysis are understood.

The combination of traditional techniques with current computational tools allows the creation of new expressive buildings with a precise control of the geometry and the structural behavior. “Brick-topia” is the first free-form thin-tile vaulted building at such a scale and open to the public. The proliferation of these new structures around the world [14] [15] [16] will hopefully help to appreciate the value of this ancient technique and will create a conscience about heritage including “Catalan vaults” to preserve them.

Figure 7: Opening of the pavilion. © Manuel de Lózar and Paula López Barba.

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