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Modern Catalan vaults: FE analyses and experimental characterization

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Abstract

Catalan vaults have always been popular in many countries. Architects such as Gaudi have made the Catalan vault a success worldwide. Substantially these vaults are built with bricks such as the “raisilla”, a thin brick that can have a thickness of one centimeter. The basic idea of Catalan vaulting technique is that a center is not necessary because, given the reduced weight of the rasilla and the nature of the mortar used for joints (often rich in gypsum), the first layer of the vault will be quickly assembled and will support the further layers and the workers. While the idea of having the joint of each new layer of the vault rotated of 45 degrees with respect to the previous layer’s joint has generally been kept, in the modern Catalan vault a mesh (steel or composite) it is often introduced, between the two external layers of bricks. This mesh operates by distributing the loads and increasing the strength against the effect of asymmetric or concentrated loads. This paper presents a study made on a new type of Catalan vault made with much thicker and stronger bricks that abandon the idea of rotating the joint direction. The vaults were firstly studied using a FEM model and then specimens of the vaults were tested in compression, flexion and shear. The results obtained were compared with more classical Catalan vault. The results seem to confirm that the Catalan technique is a fast and interesting vaulting method for modern construction.

Keywords: Catalan vaults, ecorasilla, rasilla.

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1. Introduction

Whereas people refer often to Catalan vault as a type of structure, they are ordinary vaults constructed with a particular technique that does not require a formwork or center (Benfratello et al., 2012). The idea of constructing vaults without center is very ancient (El-Derby & Elyamani, 2016).
The adobe masonry barrel vaults in Ancient Egypt were constructed with mud-bricks laid slightly tilted to the vertical such that center was not necessary (see figure 1).

Fig. 1. Mud-bricks laid tilted in an Ancient Egyptian barrel vault (in the storerooms of the Ramesseum temple). from (El-Derby & Elyamani, 2016)

The cunning idea of constructing vaults without a center of ancient masons was modified in the centuries and one of the most interesting examples is the Brunelleschi's vault of Santa Maria Del Fiore in Florence (Paris et al., 2020). The Catalan technique was popularized all over the world by Gaudi and by Guastavino that introduced the idea of using standardized thin tiles and layers of Portland cement mortar.
Vaults are structures that, due to their form, are essentially compressed. Small traction stresses might arise and, whereas in recent decades these structures were less popular, researches have demonstrated that they can be adapted in seismic regions and that they can be constructed with sustainable materials (Nanayakkara, 2020).
In the present times, Catalan vaults are still constructed by firstly building the first self-supporting layer without center or formwork (see figure 1), and, on the top of this layer other two layers of bricks with the intermediate (second) layer having the joints rotated of 45° with respect to the others. The third layer is often made with thicker tiles in order to have a larger cross section, if the structural engineer requires a larger capacity of the vault to sustain compression loads. Often, between the second and the third layer a grid is placed in the mortar connecting the layers. This grid is as thin as possible and has the purpose of reinforcing the mortar rather than distributing the concentrated loads that are rare in vaults.

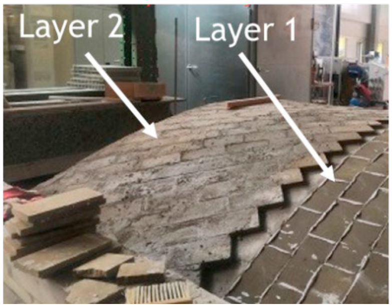

Fig. 2. A Catalan vault being built. Excavation earth bricks are used.

In this paper a modified type of Catalan vault is presented that abandons the idea of rotating the second layer of tiles and uses high strength tiles.

The disposal of excavation earth is today one of the major issues worldwide and is generally considered a waste to be disposed in landfills. In Switzerland, each year, 18 million tons of non-polluted soil is excavated, most of which is landfilled. The idea of converting this waste into a construction material is studied in many countries (Curto et al., 2020). One of the most efficient method of using the excavation soil is to produce compressed earth bricks (Làferriere, F. Viviani, 2016). The earth can be stabilized (with cement, lime or others products) or, in some cases, non-stabilized. Most of the times, modern excavation earth bricks are stabilized to regularize their mechanical properties and to reduce their sensibility to water. In recent years the rising interest on Catalan vaults has prompted the construction companies and the researchers to propose compressed earth bricks for Catalan vaults. The brick originally used to construct Catalan vaults was the "rasilla" a thin, terracotta tile (see figure 3).

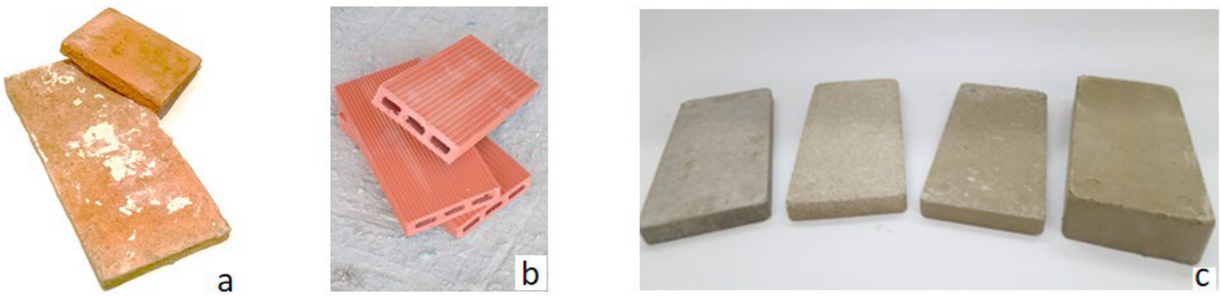

Fig. 3. Traditional terracotta "rasilla" (a), modern terracotta "rasilla" (b) and different types of Ecorasilla made with different excavation soil and different stabilizations (c)

The Ecorasilla of fig. 3 are already used to build barrel vaults and demonstrated to be a suitable alternative to terracotta bricks. Performance of Ecorasillas depends on the excavation soil available in field, on the stabilization type and rate, as well as on the manufacturing process.

Structural engineers must define the performances needed to the construction materials in order to firstly conceive and then calculate the load bearing structures. Calculation are today made by simulating the structural response of the structure -under different load combinations- with FEM software. This software, however, needs to be fed with data on the mechanical performances of the materials. Masonry structures are made with layers of brick and mortar thus the FEM model might be constructed using an approach by layers or as a homogenous material (Benfratello et al., 2010).

In this work the approach used was to collect firstly the mechanical characteristics of the materials composing the vaults (bricks and mortar) and then to simulate the behavior of a wall loaded in compression by FEM model. Specimens (walls) were then constructed, tested and their behavior was compared with the simulation.

2. Tests and simulations

Tests were made for two different type of masonry; whose characteristics were very different. The first masonry was made with Ecorasillas manufactured using a chalky excavation earth from a French excavation site, while the second masonry was made with high strength commercial bricks that had undergone to a clinkerization process. The mortar used for the Ecorasillas masonry was a quicklime-gypsum based mortar, while, for the high strength brick masonry the mortar used was a commercial M5 portland cement-based mortar. The strength, elastic modulus and poisson ratio of the bricks were tested for the earth-based bricks, while the value declared by the producer were used for the commercial brick masonry. These data were fed into the FEM models and two different softwares were used in the simulation (See Figure 4). Simulation was made with both a layered model and a homogenous model.

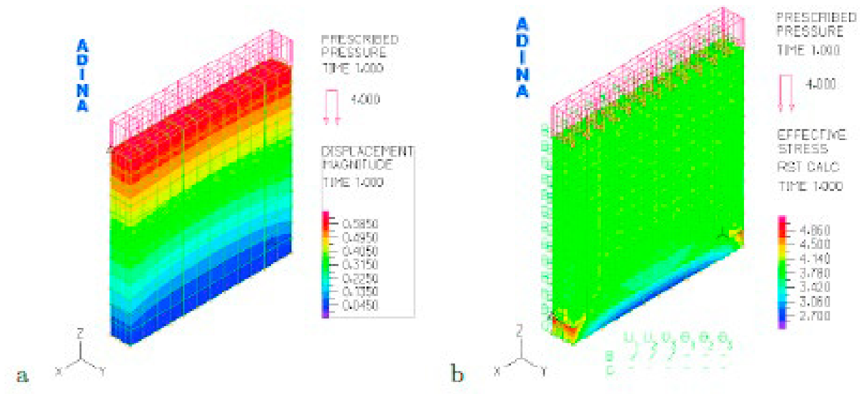

Fig. 4 An ADINA simulation of the ecorasillas walls

The tests for the structural element were different: walls were tested in compression, slabs in flexion, and a diagonal compression test permitted to study the shear behavior of the masonry elements (see figure 5).

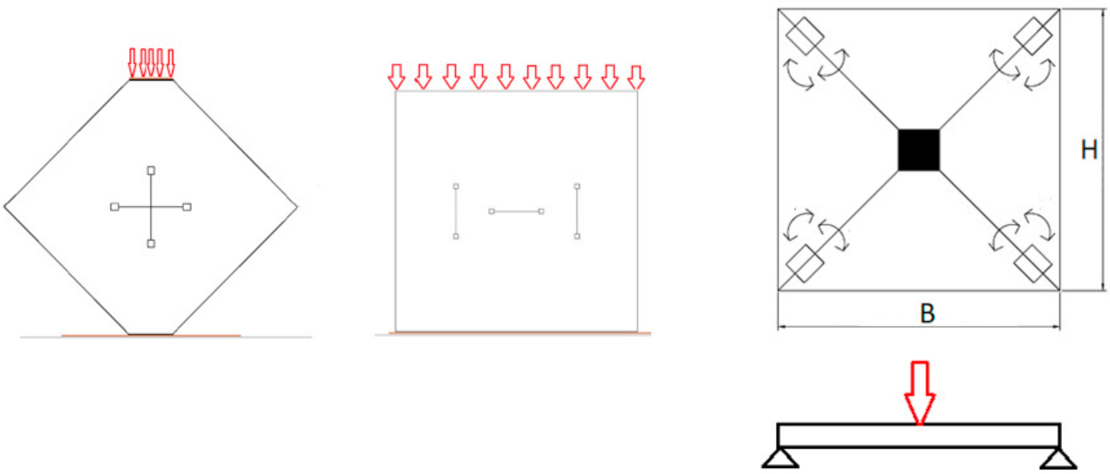

Fig. 5 Specimen tested, all specimens had the same dimensions (1mx1m).

Results of the tests demonstrated that both the materials are suitable to construct Catalan vaults, even if the mechanical performances are very different (see table 1).

Table 1. test results

	Thickness (mm)	fc (MPa)	E(GPa)	G1/3 (MPa)	Fp (kN)	w(mm)
Earth-based bricks	110 mm	6	6,4	8,8	16	55
Clinker bricks vaults specimens	145 mm	36,8	6,6	6	46	9

Three remarkable differences could be observed:
The high strength bricks were not adapted to construct vaults without a center due to their weight (some kg each). It is, however, possible to manufacture smaller and more suitable tile with the same process.
The ecorasillas were assembled by experimented masons without a specific training in raw earth masonry and Catalan vaults construction: the overall strength of the walls, although sufficient, was considerably lower than the one obtained in previous tests.
Fem simulation fitted well the test results but the value Poisson ratio has an important role in modeling and it is was difficult to obtain in small scale elements.
It can be also remarked that the failure of ecorasillas slabs (see figure 5) was more ductile than that of the high strength bricks and this is probably due to three factors:
The type of mesh used between the second and third layer (a very thin steel mesh was used for the high strength brick slabs).
The type of charge (concentrated load) with the pattern of the layers (crossed for the ecorasilla, same direction for the high strength bricks).
The high strength and stiffness of the commercial bricks and of the M5 commercial mortar.

3. Conclusions

The first results of the FEM simulation and tests on the ecorasilla elements and high strength brick elements confirm that these materials are suitable to construct Catalan vaults. It is, however, necessary to point out that the Catalan vaults construction techniques has been optimized in centuries of practical experience and research. Therefore, in both cases studied, it appeared clearly that modification of the assembly technique of the vaults brought some inconvenient: the uncrossed pattern of the layer for the high strength bricks masonry, combined with the use of a too weak steel mesh implied a more abrupt failure under flexion. In the case of the ecorasilla masonry the assemblage of the walls by not experimented mason resulted in a reduction of the overall compressive strength of the walls due to a poor transversal connection between the first and the second layer of tiles.

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