

Case Study of the Structural Behavior of a Catalan Bricks Masonry Vault

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Abstract-Catalan vaults are a peculiar type of low thickness vaulted brick masonry structure. Knowledge of load-deflection response and load bearing capacity are important aspects to consider with the aim of preserving these structural members as part of the cultural heritage. In order to investigate these aspects, complete knowledge of the constituent materials and geometry (dimension, thickness, constructive section) is necessary in such a way as to predict the load-deflection response and the effective load-carrying capacity; the latter can be determined utilizing simplified models (limit analysis) or by means of a numerical analysis (finite element method). With this aim, the structural behaviour of a Catalan vault found in an ancient building in Palermo (Italy) is studied, through an experimental investigation including material characterization and loading test on a full-scale vault. A numerical structural analysis is carried out utilizing an appropriate nonlinear finite element model. The experimental program consisted of on compressive and flexural tests on masonry units and single blocks. From the theoretical point of view, after the identification of an appropriate constitutive model based on the experimental results, a numerical analysis of the vault is performed to study the serviceability condition and the impending collapse one. The obtained results confirm the remarkable structural features of such vaults representing an important step related to the restoration of ancient structures as well as to the design of new ones.

Keywords- *Catalan Vaults; Experimental Analysis; Constitutive Model; Numerical Analysis; Structural Behaviour*

I. INTRODUCTION

Among the structural components in masonry buildings, arches and vaults deserve particular attention. They are widespread in European historical centres, and the preservation of the centres as part of the cultural heritage is a very topical subject. Because of their age and accidental causes such as earthquakes of the last centuries, these structures can suffer several types of damage. The contribution of strengthening materials and repair techniques may be required to re-establish their performances and to prevent the brittle collapse of the masonry in possible future hazardous conditions. Also, knowledge of load-deflection response and load-bearing capacity are important aspects to be considered for preserving the cultural heritage [1-3].

The stability and safety of curved structures under a given loading condition is strongly dependent on the geometry of the structures and on the mechanical characteristics of the constituent material. The masonry has negligible tensile strength, so the safety condition for masonry arches (or vaults) is achieved when the thrust line, line is kept inside each section of the arch itself. When the resultant of the internal forces moves outside the central core, the section is partially under tensile stress and a phase of high deformations starts. The consequence is the formation of a plastic hinge, which exhibits crushing of a limited portion of the masonry at the compressed edge of the arch. When the number of the plastic hinges is greater than or equal to four, the structure collapse occurs [4-7].

A case of interest, because it is widely present in the Mediterranean area, is the vault built with the tabicada technique, often adopted by many of the most important architects of the 20th century [8]. Mainly this technique has been used for building a special type of vaulted structures also known as bóveda tabicada, Catalan vaults or timbrel vaults. This technique is characterized by achieving low thickness (in comparison with the other two relevant structure dimensions) and by laying bricks lengthwise alternating with layers of mortar mainly based on gypsum. An example of this vault is shown in Fig. 1, which is present in an historical building in Palermo (Italy). The geometry and dimensions of the vault, the thickness and layers of bricks are shown in Fig. 1. By direct inspection with an endoscope, it has been found that the vault was built with three brick layers and that the filling between the vault and the roof is continuous.

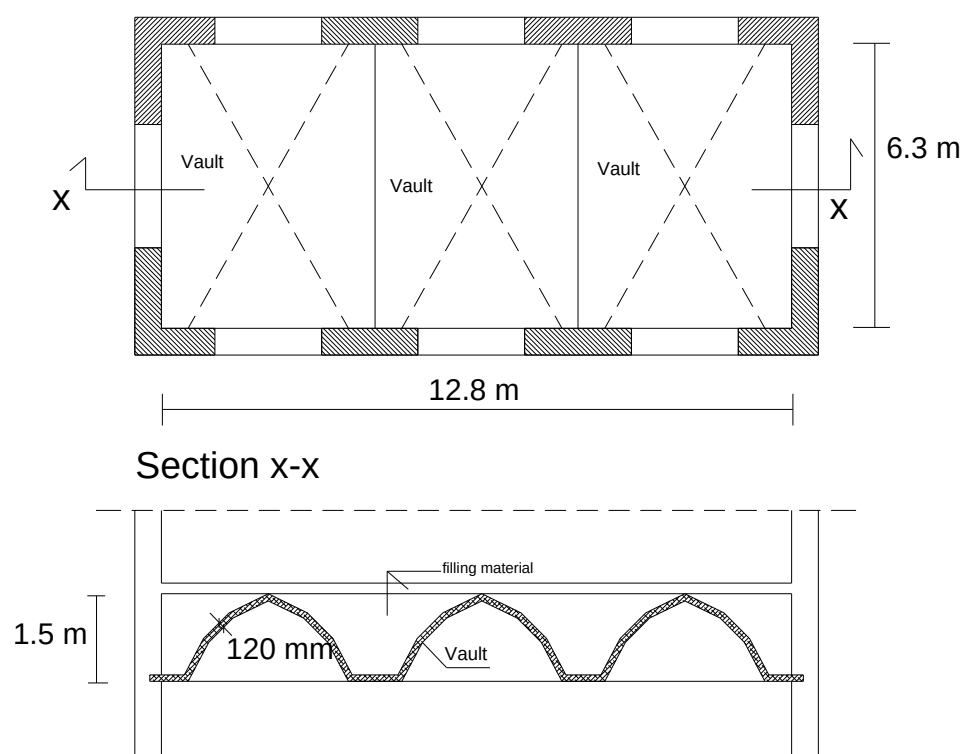


Fig. 1 Sketch of a Catalan vault found in an old building in Palermo (Italy) object of study and flexural test

Due to the low thickness feature and to the fact that the ratio between the brick and mortar layer thickness is no more than two, the overall material can be regarded as the first type of composite material adopted in the history of construction [8-9]. The Catalan vaults benefited from several studies including historical, technological [8-9] and structural behaviour aspects [10-12].

In order to investigate the structural behaviour of Catalan vaults a real case found in Palermo (Italy) has been considered. An experimental test has been carried out to determine the mechanical characteristics of the elements based on this technique (mortar and bricks). Units have been collected in situ from the real vault.

From the theoretical point of view, starting from the obtained experimental results, suitable constitutive numerical models for the materials are defined to reproduce flexural tests on units. Subsequently, coherent numerical models of the Catalan vault are defined in order to numerically reproduce the load-deformation response experimentally measured during the loading test. The results confirmed the reliability of the proposed constitutive model, as well as that of the Catalan vault, from a structural point of view. The model can be used in restoration planning and new structures design taking into account the peculiar features of this technique. In the authors' opinion, the results presented in the paper constitute a first important step towards these goals. Clearly, the results obtained cannot be regarded as conclusive, being limited by the low number of samples examined.

II. MATERIALS AND METHODS

Some samples of masonry taken from the vaults are present in a historical building in Palermo Italy. After general examination for identifying macroscopic problems as embedded tubes and macro-voids, a suitable number of specimens were collected from these samples and cut with a water circular saw. A total of six specimens of three layers were obtained and the thickness was 30 mm corresponding to the thickness of bricks. The two faces to be put in contact with the testing machine were capped with cement paste in order to smooth loading surface. After that, the samples were numbered and their geometry was identified. The mortar ratio of all samples is about 20-25% of the total thickness. In fact, each brick has a thickness ranging from 18 to 20 mm, while the mortar layer thickness varies from 6 to 8 mm, giving a total thickness of about 75 mm. From these specimens, 15 items were prepared as follows:

- three cubes with a side length of 20 mm for compressive strength tests (the size of specimens was the same of the thickness of bricks);
- three prisms of mean dimensions 120×18×240 mm, to be tested under a three-point bending in order to characterize the tensile strength of the brick;

- six masonry cubes with a side length of 120 mm to be tested under compression both parallel and orthogonal to the layer;
- three masonry prisms of mean dimensions 370×115×1010 mm to be tested under a four-point bending in order to characterize the flexural masonry behaviour.

The number of specimens was limited because of the relative difficulties to extract the samples from their historical structure.

The petrographic and chemical investigations were performed using the Olympus SZX-ILLK200 optical microscope and the Ital structures APD2000 XR Diffractometer. The XRD patterns are shown in Fig. 2, while the petrographic description is shown in Table 1. The XRD analysis was performed on two samples: one obtained from the external layer (plaster) and the other one from the internal layer (mortar). The results showed in Fig. 4 confirm the use of a gypsum mortar for the internal layer. This type of analysis is of interest in this context to have some additional information referring the properties of materials constituting the vault all aspects influencing the load-deflection respond of the vault and its ultimate state if in the case of degradation of materials.

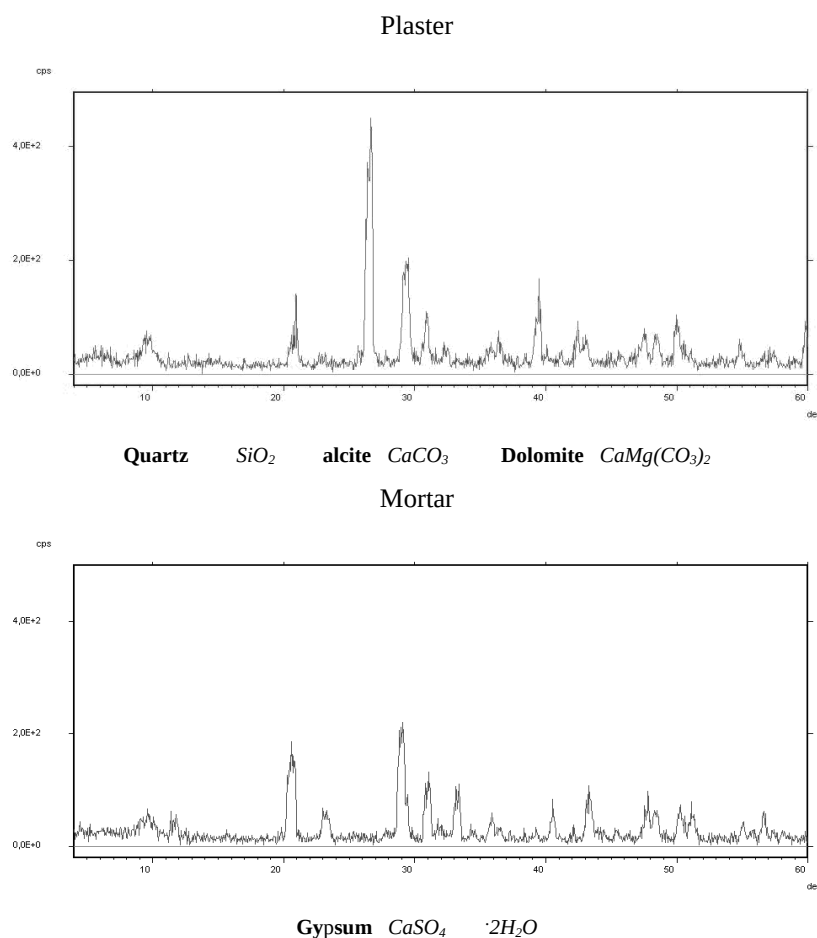


Fig. 2 Mineralogical composition of plaster and mortar estimated by XRD technique

TABLE 1 MECHANICAL CHARACTERISTICS OF THE SPECIMENS

Specimen	f_{cm} (MPa)	0	085	E (MPa)
1	13.20	0.0045	0.0085	4400
2	12.00	0.0032	0.0043	4300
3	11.80	0.0022	0.0035	4460
Mean	12.33	0.0033	0.0054	4386

From the theoretical point of view two numerical modelling operations were performed using the Finite Element software ADINA (version 8.8.5). The first one was used to describe the flexural tests on the units. However, the second one is used to describe the structural behaviour of the vault. In the first step, attention was paid to the choice of the best technique for modelling units by using, alternatively, an equivalent homogenous ideal material [13-15] and multi-layered material reproducing each layer as a homogeneous material with its own special characteristics.

In any case to model the bricks (constituting each layer of the specimens) a four-node brick element was selected using ADINA software [16]. The mechanical characteristics of the brick were deduced from the tests described in the previous section referring to the average curves. The mortar was chosen adopting values deduced from flexural tests.

Once the material behaviour was identified and correctly modelled in a numerical way, the structural behaviour of a real vault was investigated numerically and compared with the experimental results obtained with the load tests previously described.

The vault was numerically modelled in two different ways using alternatively:

- a homogeneous material with four-node brick elements, considering the real total thickness for the structure geometry;
- four-node shell elements with five layers with linear elastic materials and considering the mid-surface of the vault as the reference geometry.

The numerical modelling included both layered and homogeneous materials. In the case of homogeneous material, the numerical model was constituted by 21368 3D four-node elements, while in the case of layered material 20432 shell multilayer elements were used. In order to perform the numerical analysis, the loading model has been defined as the superimposition of a pressure spatially distributed in a quadratic way (maximum at the abutments and minimum in line with the key brick) related to the permanent actions (the filling, the roof and the dead load) and a uniformly distributed pressure equal to 2 kN/m² in order to simulate the overload actions. The structural performance was measured by calculating the principal stresses acting on the material.

III. MATERIAL CHARACTERIZATION

All compressive tests on cubes and prisms were conducted on the Zwick & Röll Z600 universal testing machine. Collected data were evaluated using the TestXpert software (version 11.2), which is supplied by the same firm. The crosshead speed used throughout the experiment was 0.15 mm/min. No specific protocol was followed to perform tensile and flexural tests because dimensions of specimens extracted from real structure are not standard dimensions according to the most common codes on testing construction materials.

A. Compression and Indirect Tension Tests on Masonry Bricks

The graph stress against strain (Fig. 3), shows a quasi-brittle response for all tested. In the first branch of the stress-strain curves, the material exhibits a linear elastic behaviour with a gradient (modulus of elasticity) of 8 GPa. The average peak stress and their corresponding strain were 11.66 MPa and 0.0033 respectively.

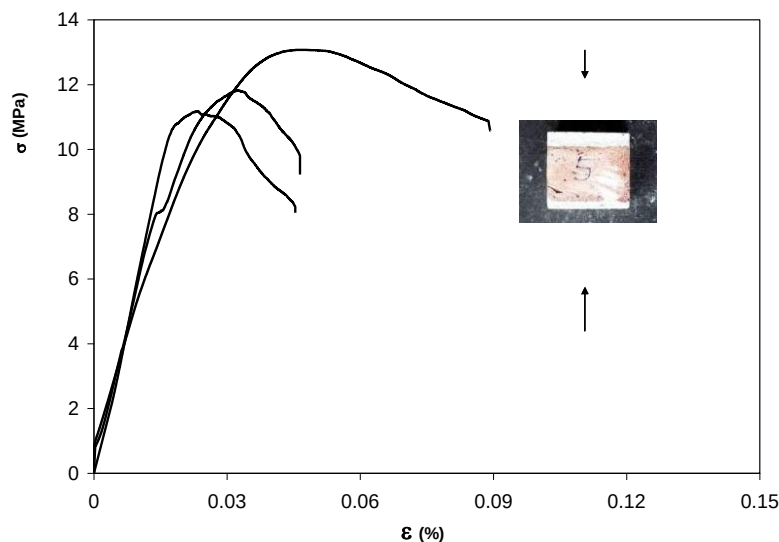


Fig. 3 Compression test on masonry brick

In order to characterize the tensile strength of the material, a three-point bending test was performed on three different bricks collected from the same samples as in the compression test. Specimens were tested with a shear span-to-depth ratio of 2.33. The specimens were slender enough to expect flexural failure. The tests were performed with the same set-up and characteristics as previously described. The flexural response of the material, shown in Fig. 4, was quasi-brittle. Values measured for single specimens were very closed to the average value of the three specimens tested. The modulus of rupture

(MOR) of these bricks can be determined by the equation: $MOR = \frac{3 \cdot P \cdot a}{2 \cdot b \cdot t^2}$, where P is the load that breaks a rectangular specimen of length a , and cross-section $b \cdot t$, in the 3-point bending test arrangement shown in Fig. 3.

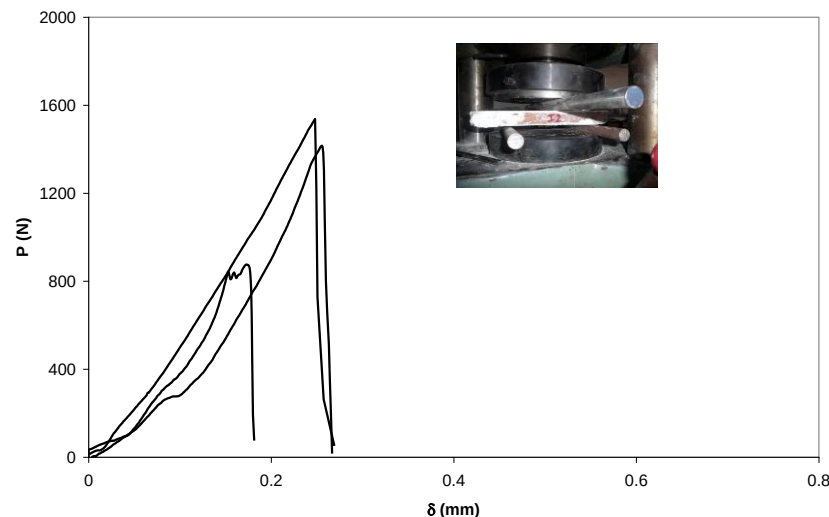


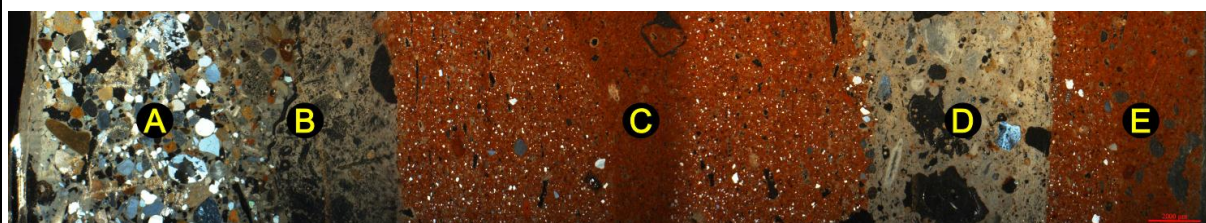
Fig. 4 Three-point bending test on masonry brick

Table 2 gives the compressive strength f_{cm} , the corresponding strain ε_{cm} , and the strain $\varepsilon_{0.85}$ measured at $0.85 f_{cm}$ (in the softening branch). The module of rupture in flexure (MOR) values was 5.12, 4.50 and 2.59 MPa, respectively.

TABLE 2 PETROGRAPHIC ANALYSES

Level	Thickness (mm)	Aggregate/Binder/Pores or Temper/Matrix/Pores ratios	Description
A	10	(A/B/P): 65/25/10	Lime mortar: the aggregates ($d_{min} = 0.1\text{mm}$; $d_{max} = 2\text{ mm}$) are made mainly of quartz and to a lesser extent of micrite and spar (maximum diameter = 5 mm). Sphericity and roundness are high. Sorting is high.
B	4	(A/B/P): 20/55/25	Mortar of gypsum: the aggregates, poorly sorted ($d \approx 2\text{ mm}$), are made of microcrystalline gypsum (the main fraction) and subordinately fine grained selenitic gypsum.
C	20	(T/M/P): 25/70/5	Fictile material characterized by a medium birefringence of the matrix. The inclusions are mainly of silt and rarely of monocrystalline quartz ($d_{max} = 0.8\text{ mm}$).
D	4	(A/B/P): 20/55/25	Mortar of gypsum: the aggregates ($d = 0.5 - 3\text{ mm}$) are made of gypsum, both microcrystalline (the main fraction) and selenitic. Macropores are frequent ($d = 5\text{ mm}$).
E	> 20	(T/M/P): 25/70/5	Fictile material characterized by a medium birefringence of the matrix. The inclusions are mainly of silt ($d \approx 0.02\text{ mm}$). Numerous monocrystalline quartz grains are present ($d = 0.5-0.9\text{ mm}$) in small clusters.

Surface of plaster, masonry and brick viewed in reflected light at 7x magnification



Scale 1:100000

IV. UNIT CHARACTERIZATION

To characterize the specimens in compression and in flexure, appropriate tests under displacement control were carried out with a speed of 0.5 mm/min.

Six masonry prism specimens with mean sides 120 mm long were obtained from larger masonry three-layer samples by cutting the latter with an appropriate saw. The specimens had the same thickness as the vault. Friction between contacting surfaces is prevented by applying a thin layer of gypsum paste. Three of these specimens were tested under compression parallel to the layers and three others under compression orthogonal to the layers. Strains were measured by using three linear voltage displacement transducers (LVDTs) mounted on the specimens with a gauge length shorter than the height of the specimens.

A. Compressive Tests on Units Loaded Parallel and Perpendicularly to the Brick Layers

The stress-strain curves of specimens tested in compression parallel to the layers (Fig. 5(a)), show that the material was stressed just as it is in a real vault. Regarding the trend of the response, it clearly appears that an initial linear elastic behaviour exists followed by a nonlinear branch up to peak stress. Then a strain softening behaviour was observed.

The stress-strain curves of units tested perpendicularly to the layers (Fig. 5(b)) show that the role of the mortar was more evident in terms of deformability of material and the strength was less than that measured parallel to the layer.

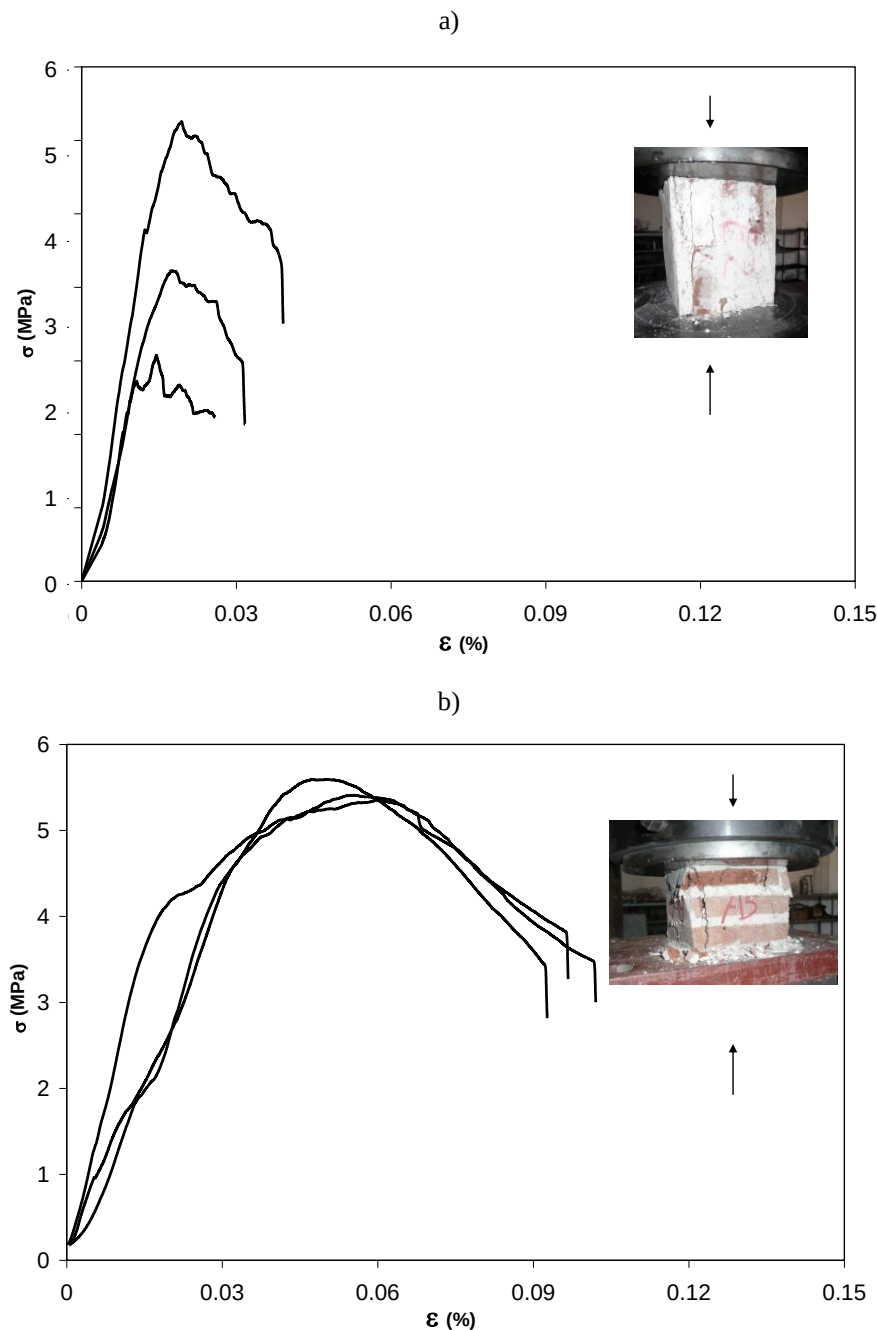


Fig. 5 Compression test on masonry prism parallel (a) and orthogonal (b) to the layers

The mechanical properties of these tested specimens are reported in Table 3.

TABLE 3 MECHANICAL CHARACTERISTICS OF THE SPECIMENS FOR COMPRESSION TESTS

specimen	Parallel to joint mortar	f_{cm} (MPa)	ε_0	ε_{085}	E (MPa)
1		6.24	0.0019	0.0028	1670
2		4.11	0.0018	0.0027	1650
3		2.98	0.0015	0.0020	1680
mean		4.43	0.0017	0.0025	1666
specimen	Perpendicular to joint mortar	f_{cm} (MPa)	ε_0	ε_{085}	E (MPa)
4		5.50	0.0049	0.0072	1610
5		5.40	0.0055	0.0078	1425
6		5.36	0.0059	0.0076	1410
mean		5.42	0.0054	0.0076	1481

The behaviour exhibited during the compression tests showed a classical trend. After an initial phase in which the plates of the testing machine adapted to the specimen surface, the material presented linear elastic behaviour ending at about 2.5 MPa with a tangent modulus ranging from 0.33 GPa to 0.50 GPa. At the end of the elastic phase a nonlinear strain hardening occurred until the ultimate stress was reached. Finally, a strain softening was present until the end of the test.

It is worth noticing that the behaviour of the masonry specimens is quasi-brittle with the physical meaning that it occurs with progressive separation between the layers and evident buckling phenomenon of single brick. In general, the fractures started where the thickness of the mortar was reduced and on the interface between bricks and mortar.

B. Flexural Tests on Units Loaded Perpendicularly to the Brick Layers

Three specimens, constituted by three layers, having the same thickness as the units tested in compression, were tested in flexure in four-point bending tests. The test schemes, the bending apparatus and results (load-displacement) are shown in Fig. 6.

The results allowed to evaluate the overall bending traction resistance of the material under investigation. By comparing this result with that obtained in the three-point bending test on the bricks it can be deduced, as expected, that the tensile strength of the masonry is about one order of magnitude lower than that of the bricks and that this has to be ascribed to the loss of continuity and to the influence of the mortar. It is worth noticing that the bending tests described were performed on samples with plaster, which is the situation faced by the material during the structure's lifetime. When the ultimate force P is

known, as well as the shear span and the cross-section ($b \times t$), the modulus of rupture proved to be: $MOR = \frac{6 \cdot P \cdot a}{b \cdot t^2}$. The

MOR values obtained were 0.99, 0.82 and 0.74 MPa respectively.

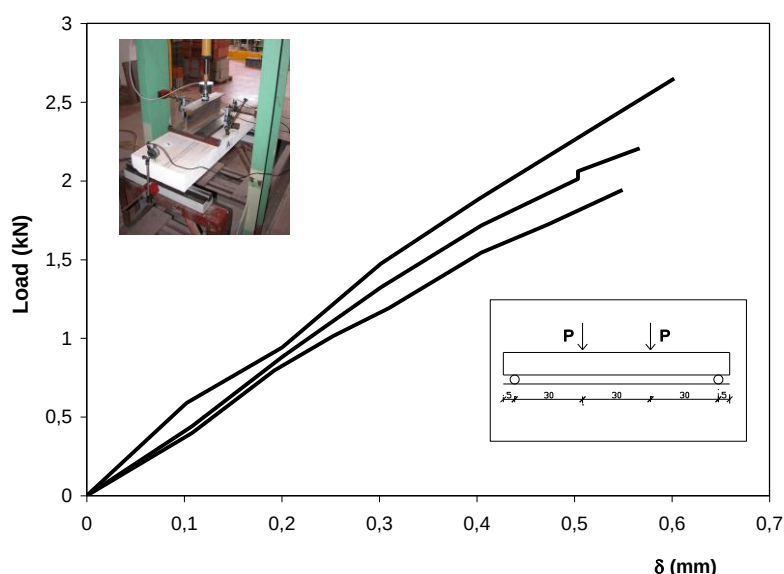


Fig. 6 Four-point bending tests

V. LOAD TEST ON CATALAN VAULT

A load test was performed on the vault system depicted in Fig. 1. The vault had a length of 12.80 m, a width of 6.30 m, an intrados rise of 1.50 m and a thickness of 120 mm including plaster. The vault was characterized by the presence of six lunettes equally spaced along the vault length, the lunette width being equal to 3.30 m. Finally, two tie steel rods about 4.00 m long were present and located symmetrically to the vault transversal midsection. The vault examined in this section was subjected to a load test due to distributed load (ranging from 0.0 to 4.0 kN/m²) acting on the over-roof (Fig. 7). During the test the vertical displacements of two points (Fig. 7a) were measured. The measurement set-up was constituted by three HBM WTS20 gauges connected to an HBM UPM60 device. In order to check the tie rod's effectiveness an HBM strain gage was positioned in the middle section of one of the rods and connected to the device referenced above. The load was applied by using water flexible tank (rubber dinghy) and therefore it was possible to control accurately the application of external load, which was uniformly distributed.



Fig. 7 Loading scheme and test set-up for loading test on Catalan vault

The experimental results in terms of uniform load-deflection curves are reported in Fig. 8. Linear elastic behaviour is observed as expected for serviceability conditions.

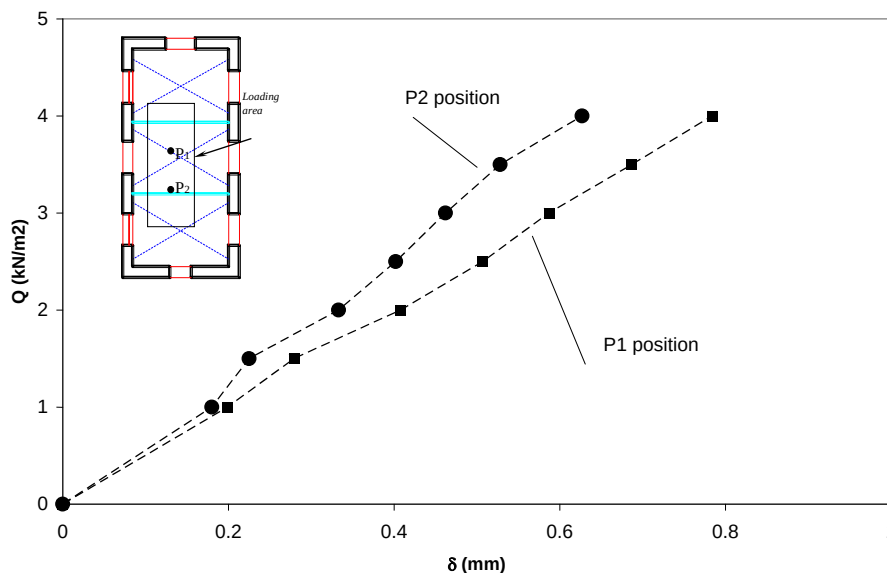


Fig. 8 Load-deflection response of vault

VI. NUMERICAL MODELING AND COMPARISON WITH EXPERIMENTAL RESULTS

The load-deflection response in flexure of the units obtained numerically with the homogenous and layered model and the experimental response (average curve of the three tested specimens) is shown in Fig. 9.

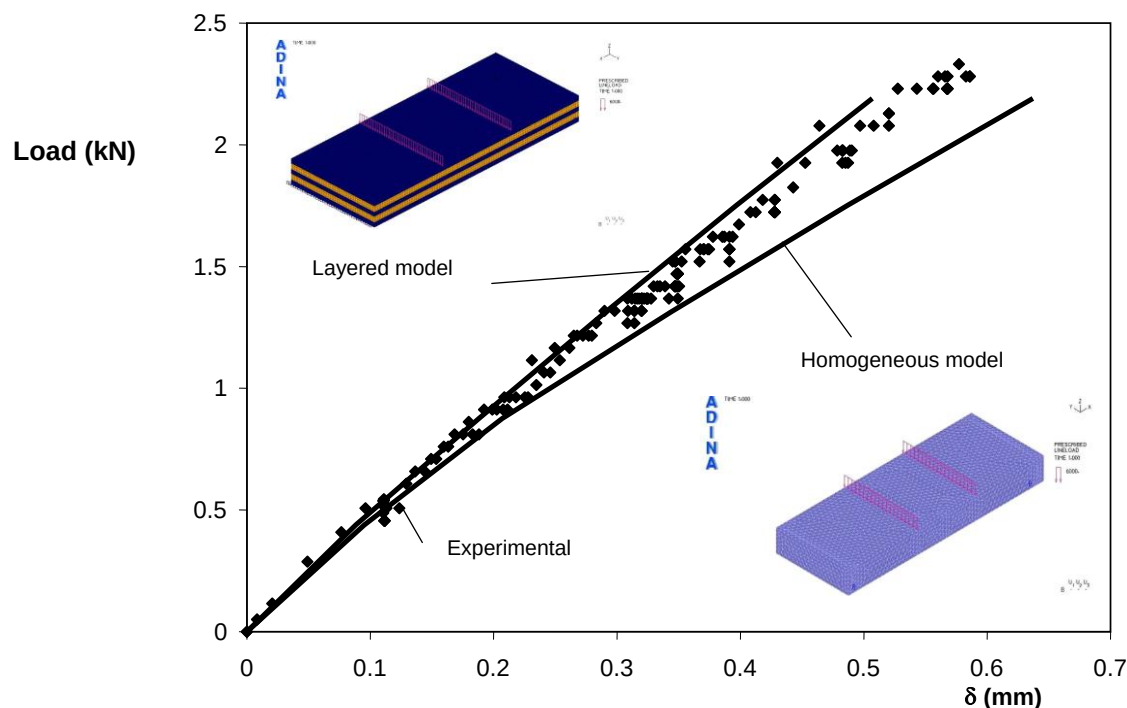


Fig. 9 Bending test numerical model

Fig. 10 shows the load deflection response of the vault determined both experimentally and numerically. A comparison shows that the numerical model accurately reproduces the experimental response and the layered numerical response gives the best prediction.

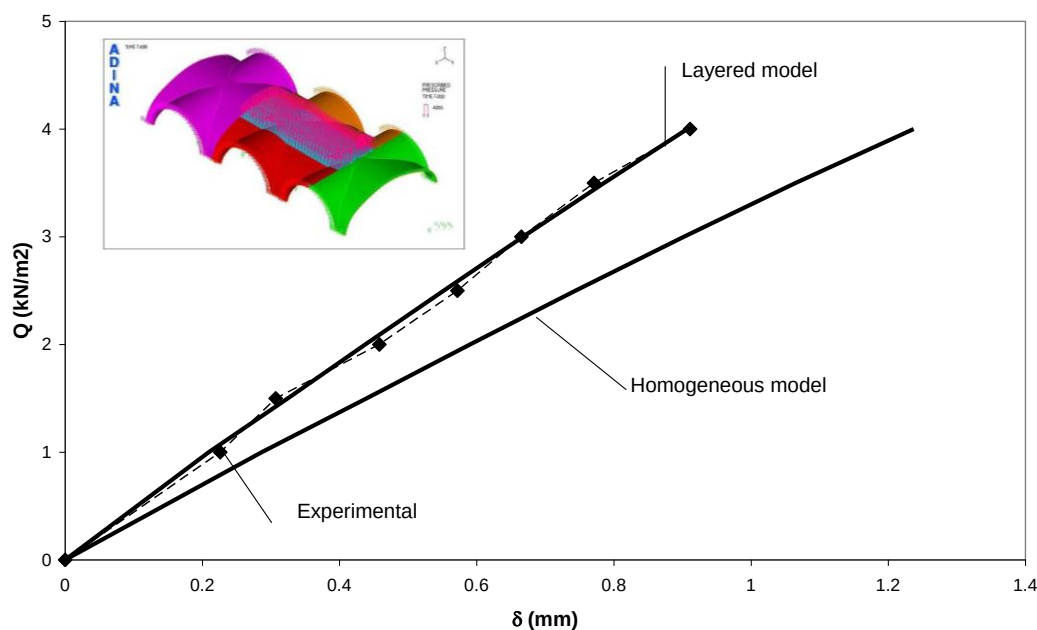


Fig. 10 Comparison between experimental and numerical results

Material characteristics for homogenous material were those observed experimentally from compressive tests. Moreover, non-contact element was considered for layered material and perfect adhesion between mortar and brick was considered to perform structural analyses. The numerical result in term of maximum positive principal stress was equal to 0.078 MPa (negligible tension), and the minimum negative principal stress (compressive stress) was equal to 1.55 MPa.

VII. CONCLUSIONS

The present work is focused on the structural behaviour of Catalana vault constructed with the tabicada technique.

The results reported in the present paper confirm the role played by the tabicada technique, with special reference to the Catalan vaults, in the history of architecture; the effectiveness of this ancient technique adopted and revised by important architects in the 20th century in many of their masterpieces is known. This analysis highlights another very important characteristic of this technique related to its modernity and to the strategy to be used in the restoration of ancient architectural-structural elements realized adopting the tabicada technique. In this framework, it is fundamental to correctly characterize the mechanical behaviour of the structural elements in order to evaluate the real stress levels and, therefore, their safety factor when facing a restoration design. Moreover, coherent mechanical characterization allows one to design correctly new structures taking into account both the requirements of current structural codes and the peculiar features of the tabicada technique.

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