

Experimental analysis of "bovedas tabicadas"

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SUMMARY. A particular type of vaulted structures, known as bóvedas tabicadas (Catalan vaults), made with alternate layers of bricks and mortar and characterized by a very low thickness in comparison to the other two dimensions, are studied. The research has been faced under the historical aspect as well as under the mechanical one, developing experimental and numerical analysis regarding real existing structures. In particular, the experimental analysis, performed by effecting compression and bending tests on samples taken from a real structure, has been devoted to the constitutive material identification and the characterization is made by considering the material as an ideal homogeneous; further experimental tests have been made on a real vault and the related numerical analyses have been developed by utilizing a suitable FEM discretization.

1 INTRODUCTION

The present paper is devoted to the study of the so-called "bòvedas tabicadas", representing one of the most common traditional building techniques which found their better expression in the work of some of the worldwide known Spanish architects (first of all Gaudì) at the end of XIX century [1-4]. The fundamental structural features of these vaults are linked with a very low thickness with respect to the medium surface dimensions and with their special typology. Usually, the relevant structure is constituted by three layers of bricks of small thickness with mortar even if structures with four layers of bricks can also be found. It is to be emphasized that elements with two layers are characteristic of partition walls rather than of thin vaults. In last years it has been pointed out that in Sicily this technique has been widely adopted in early centuries also for setting up very important buildings such the "Palazzina Cinese" in Palermo and the "Villa Butera" in Bagheria. The experimental analysis of specimen collected from an existing structure whose thickness is obtained with three layers has been already performed by the authors [5]. Aim of the present paper is to supplement the experimental study by performing compression tests on specimens obtained from samples with thickness of both two and four layers collected from other existing structures and by executing suitable load tests on real vaults, in order to identify a coherent mechanical model for the material to be used for the necessary comparison between the numerical analysis and the experimental measurements. The obtained results, together with the previous ones, allow us to validate the chosen ideal equivalent homogenous model for the material, emphasizing some technological aspects affecting the experimental response, first of all the influence due to the stiffness of the overhanging slab. The obtained model can be adopted in the safety evaluation and in restoration of existing structure as well as in design of new structures [6].

2 LOAD TEST AND NUMERICAL ANALYSIS FOR A BARREL VAULT AT VILLA BUTERA IN BAGHERIA

During the restoration works effected at Villa Butera, it was possible to detect the presence of a large variety of building techniques, among which several catalan vaults with tree layers of bricks. The endoscopic investigation showed the presence of a rigid slab connected to the underlying vault by suitably disposed vertical limestone elements. The load tests were carried out as prescribed by the relevant Italian structural code simulating the presence of loads identifying the so-called serviceability conditions suitably amplified. In Figure 1 the relevant vault is shown, while Figures 2 and 3 show the utilized experimental test equipment. During the test a maximum load value equal to 4000 N/m^2 was reached, and it was carried out in ten subsequent steps each characterized by a load increment equal to 400 N/m^2 . After each load step the time necessary for the stabilization of the displacement has been expected in order to be acceptable the reading in the displacement gauges.

The obtained experimental results are reported in the load-displacement diagram plotted in Figure 3. In particular, the displacement related to the middle point of the vault has been reported as function of the acting load in the cited figure. The other measurement effected at $1/4$ of the total span provided qualitatively analogous behaviour. The obtained results clearly show the substantial linearity between the vertical displacements and the applied loads. At the end of the load test, the measured displacements were equal to 0.952 mm and 0.292 mm , respectively. The residual displacement at the end of the test was equal to 6.3% and 5.2% of the total reached during the test, respectively, for the centerline and for that at $1/4$ of the total span.



Fig. 1: Catalan barrel vault on the ground floor of Villa Butera.



Fig. 2: Setup used for the load test.



Fig. 3: Measurement setup for the load test.

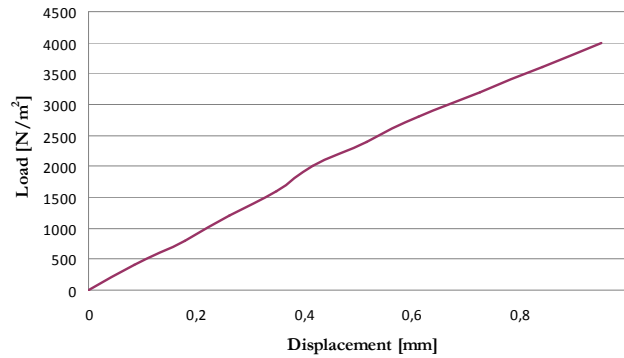


Fig. 4: Results of the load test on the existing barrel vault.

The numerical analysis was carried out on the grounds of an ideal isotropic mechanical model equivalent to the real non-isotropic one, modeling the vaulted structure as a continuous solid. According to the geometric data a three-dimensional model of the vault was developed on a CAD software. This model was imported in a FEM software, ADINA[®] 8.7.5, adopting as parameters of the CONCRETE model the following ones: Young modulus 1.7 GPa, limit compression strength 3.0 MPa and limit tensile strength 80 kPa. The vault was discretized into 221,463 3D finite elements with four nodes.

The obtained results can be represented through the field of the vertical displacements and those of the principal stresses σ_1 and σ_3 (Figures 5).

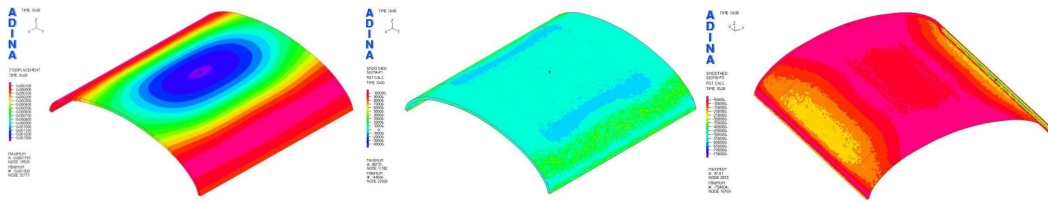


Fig. 5: a) vertical displacement field; b) principal stress σ_1 field; c) principal stress σ_3 field.

As it can be seen from the obtained graphs reported in Figure 6a, for the maximum value of load reached, the vertical displacement was found to be equal to 0.952 mm for the experimental test and 1.3 mm for the numerical analysis. It follows that the real structure exhibits a stiffer behaviour than the one modelled in the computational analysis. The difference between these results is certainly due to two different components that were not currently considered in the computational stage: the first one is represented by the vertical elements connecting the vault with the overhanging slab, whose contribution has been estimated only from a gravitational point of view, while they also constitute a stiffening able to restrict the displacement of the vault; the second is represented by the weight and the contribution of stiffness that the above structure of the screed and the flooring supplies to the vault, which, as demonstrated by actual data derived from wide experience, usually affects the test with an incidence of 25%. Taking into account the contribution of the above referenced components on the overall structure stiffness, the numerically obtained vertical displacements can be reduced by 25%, thus leading to results very close to those of the experimental test performed in situ. In Figure 6b the experimental and numerical results are compared taking into account the above described contributions.

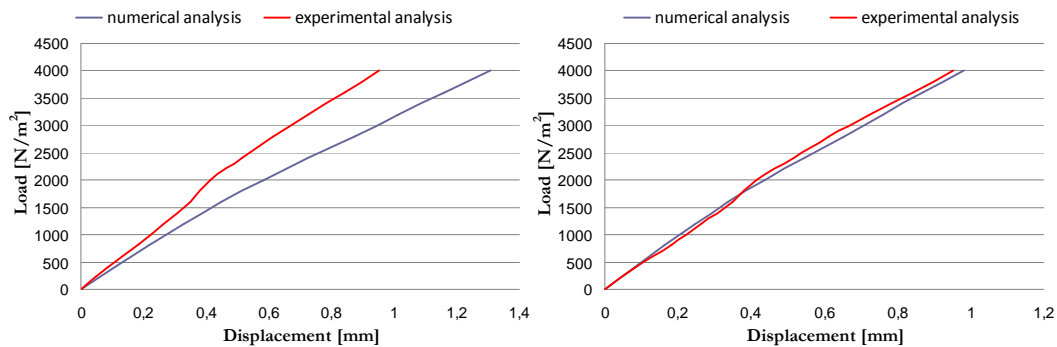


Fig. 6: Comparison between experimental and numerical results without (a) and with (b) the contribution of stiffness of the slab above

3 CONCLUSIONS

The present paper has been devoted to some advance in the study of catalan thin vaults in order to improve the knowledge of their mechanical features and behaviour through new experimental and numerical procedures. In particular, new compression experimental tests have been effected on the material, as well as further load tests on existing structures. The numerical modeling carried out on the barrel vault of Villa Butera, besides confirming the results of the in situ load test, has demonstrated that the resultant stress fields are compatible with those characterizing the material, being the maximum and minimum obtained values within the range prescribed for the material model, highlighting the good response of the relevant structure to the imposed load condition. The results may, however, be improved by acquiring more and more actual information on the geometry and consistency of the ceiling, especially with regard to the type of abutment at the vault extremes, the nature and distribution of stiffening vertical elements placed on the extrados of the vault, and the type of slab over the relevant vault. The effected experimental and computational investigations provided a deep enough knowledge of the mechanical behaviour of catalan vaults and of the constitutive law that characterizes the catalan masonry, although the assumption of homogeneous and isotropic material. The obtained results allow us to confirm what it has already been expressed by the treatises and more generally by the recent scientific literature on catalan vaults, proving the efficiency of these vaults in relation to their small thickness.

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