EXPERIMENTAL AND NUMERICAL INVESTIGATION ON TRM REINFORCED MASONRY VAULTS SUBJECTED TO MONOTONICAL VERTICAL SETTLEMENTS

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ABSTRACT

The present work is aimed at studying the efficiency of Textile Reinforced Mortar materials (TRM) for repairing ancient curved structures. To this scope, a timbrel masonry cross vault was constructed and tested at the ICITECH laboratories of the Universitat Politècnica de Valencia (Spain). The experimental investigation comprised the testing of the vault and its following repairing by means of TRM materials. During the first test, the collapse was characterized by the formation of a deep crack along the elliptic diagonal arch connecting two opposite supports. The TRM strengthening comprised an extrados layer composed by a 25x25 mm glass grid embedded into two approximately 5 mm thick layers of a mortar matrix. A direct comparison of the experimental results obtained showed the positive effect of the TRM strengthening on the global structural behaviour of the vault. The TRM strengthening was able to increase the peak loads and prevent the formation of cracks along the extrados surface of the structure. Also, a 3D macro-modelling FE strategy was adopted to study the behaviour of the structure during the tests. The models were developed by means of the FE commercial software Abaqus. The masonry support as well as the TRM retrofitting were simulated by means of shell elements. Finally a satisfactory agreement was obtained between the experimental and the numerical results.

Keywords: Full-scale timbrel vault, Experimental investigation, Numerical Analysis, Cyclical settlement, Textile Reinforced Mortar (TRM) material.

1. INTRODUCTION

Masonry cross vaults are part of the architectural construction heritage of the whole Mediterranean area. They have been built during the centuries using different materials, shapes and construction techniques. In particular, masonry cross vaults have been used with a covering function in churches and historical palaces. Some remarkable examples of such impressive structures are presented in Figure 1. Despite their quite widespread adoption during the past centuries, the scientific knowledge about their structural behaviour is still at an embryonic stage. A first attempt to explain their structural behaviour has been conducted by Willis [1] and later by Viollet-le-Duc [2] and Sabouret [3]. Their primary aim was intended to focus on the identification of the structural function of each element composing a masonry vault and in particular, of ribs. As a matter of facts, masonry cross vault

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could be ideally subdivided into two main categories: groin vaults and ribbed vaults. The main
difference between them is represented by the presence of ribs.

As reported in [4], Romanesque builders slightly modified the groin vault’s building technique to solve
the difficulties related to their construction adding diagonal ribs as a partial bearing stiffener of the
webbing. The solution helped to increase the span of the vaults, to further reduce their thickness and
to add an lightweight aesthetic effect as well. This modification was rapidly adopted and ribbed vaults
became quite popular during the past centuries. Considering how quickly they spread and the
quantity of historical buildings nowadays certifying their adoption, the structural role of ribs has
always call the attention of researches. A first explanation of the role of ribs imputes to voussoir ribs
the role of a stone-centering system which replaced the traditional wooden ribs for transverse arches
and groins. This finding confirms the idea that ribs have been used to sustain the masonry webs both
before and after the vault is built. In addition, the disconnection between stone-vousoir ribs and
masonry webbing helped to point out the capacity of masonry vaults to adapt to changes in loads
highlighting the crucial role played by equilibrium in their stability. Given the scarce theoretical
background at disposition of the masons who built these structures, it is reasonable to assume that
they adopted rules of thumb to estimate the limit state of the structure. The impossibility to know the
structural design principles employed during the past centuries justifies why the function of the
different elements in a masonry cross vault is still debated. It is also clear that such structures do not
match the requirements of the current guidelines and therefore the prediction of their structural
behaviour became crucial especially in seismic prone areas. One of the most useful approach is
represented by the so-called “equilibrium approach”. It has been adopted mostly to analyse the
structural behaviour of masonry arches and to predict their load bearing capacity. This approach,
rigorously formulated by Heyman [5], postulated that an arch is able to stand as long as a thrust line
can be found that fits within its section. Subsequently, various researches tried to extend the same
approach to the analysis of masonry vaults introducing the idea of a thrust network instead of a thrust
line. Although this latter research line has become very popular in the recent years, the pioneer in this topic was O’Dwyer [6]. Indeed, several authors analysed further the possibility to extend its funicular analyses to tri-dimensional structures. In this framework, Thrust Network Analyses (TNA) [7] represents advanced developments of the work proposed by Heyman. This family of strategies allows the estimation of the collapse load, the active failure mechanism and the thrust network by means of a standard linear programming problem, which maximizes the failure multiplier under equilibrium constraints and the admissibility of internal actions. More recently, continuum-based approaches (FEM) and Discrete Element Strategies (DEM) have been proposed to study the behaviour of masonry vaults. One of the most critical drawbacks of FEM strategies is related to the prohibitive computational cost when dealing with complex geometries. As a matter of fact, one of the most fascinating approach is represented by the so-called micro-modelling strategy. This approach allows simulating the constituent materials separately making possible to describe most of the peculiar aspects of masonry, for instance its orthotropic behaviour. However, due to the high number of FEs involved into the simulation, this kind of approach is often not suitable when analysing full-scale masonry vaults. On the other hand, DEM resulted particularly suited on this regard. Indeed, using DEM approaches, masonry structures can be modelled as a combination of rigid blocks connected by non-linear interfaces. DeM’s major advantage in dealing with masonry is that it can lump all the nonlinearities at the level of the mortar joints. This assumption is highly acceptable for old unreinforced masonries but could be a significant limit for reinforced structures. In this framework, the experimental testing of full-scale masonry vaults plays a crucial role towards a better understanding of the behaviour of such structures. In particular, only in scale prototypes have been tested with respect to in plane or out of plane supports’ distortions. Even less experimental investigations have been carried out to understand the behaviour of masonry vaults when subjected to soil-induced movements. In order to cover this lack of knowledge, the present work discusses the experimental and numerical investigations developed at the ICITECH laboratories of the Universitat Politecnica de Valencia (Valencia, Spain) with respect to a masonry timbrel vault unreinforced and reinforced with Textile Reinforced Materials (TRM) and subjected to a vertical settlement in one of its supports.

2. EXPERIMENTAL INVESTIGATION
2.1 Set-up and monitoring apparatus

This section is intended to describe the experimental campaign developed in one of the laboratories of the ICITECH (Valencia, Spain). The investigation comprised the unreinforced and TRM (Textile Reinforced Mortar materials) reinforced testing of a full-scale masonry cross vault subjected to a monotonically increased settlement in one of its supports [8]. It is worth mentioning that, the geometry of constructed vault was inspired by the ones partially collapsed in the Church of San Lorenzo de Castell de Cabres (Spain). The masonry cross vault herein analysed has been constructed following a peculiar procedure. Indeed, timbrel vaults are commonly built laying down bricks in a flat position (230 × 110 × 26 mm³) and interposing various layers of mortar materials. In detail, the vault comprised four lateral arches composed of four layers of bricks and three layers of mortar, whereas the webbing was constructed with two layer of bricks placed perpendicularly and one layer of mortar. This type of structure are known as timbrel vaults. They were first used in the Catalan region of Spain and are characterized by a peculiar construction technique characterized by two or more layers of
tiles laid flat and held together by thick layers of mortar. It is important to underline that, the peculiar disposition of different materials is able to help the layered masonry to work as a homogeneous unit, in spite of the differences related to the stiffnesses and strengths of the constituent materials. The final masonry arrangement of the tested vault is visible in Figure 2(a). As showed in Figure 2(a), the vault rested on four concrete supports, labelled herein as S1, S2, S3 and S4. A mechanical system composed by two steel plates and bearing balls allowed the application of different boundary conditions to each vault support. In detail, supports S2 and S4 were free to move along the horizontal plane only, support S3 was completely fixed, whereas support S1 was similar to supports S2 and S4 but with an imposed displacement applied. The concrete bases were placed at the corners of a 4 × 4 m square connected by four 3.6 m diameter semi-circular lateral arches. The arches were approximately 1.8 m high and the total height of the structure considering the concrete bases reached 2.51 m. Furthermore, all the supports of the vault have been connected by means of a steel bracing frame composed by HEB 140 profiles hinged to the bases of the vault. The system was designed to prevent the development of possible premature diagonal failures of the vault and to simulate the partial lateral constraint effect produced by adjoining vaulting systems. The experimental investigation comprised the application of a monotonically increasing downward vertical displacement in support S1 to mimic a soil-induced settlement of one vault ‘support. The settlement histories applied to the vault before and after the application of the strengthening are depicted in Figure 2(b) and Figure 3(b). The laboratory investigation was organized in three phases: (i) construction and testing of the timbrel vault with a maximum imposed displacement of 40 mm, (ii) repairing and application of a 10 mm thick layer of Textile Reinforced Mortar materials (TRM) on the extrados of the vault (iii) testing of the repaired vault with a maximum imposed displacement equal to 80 mm. In both cases, the settlements were applied by means of two mechanical jacks located at the bottom of the steel base of support S1 and manually synchronized in order to avoid the application of undesired rotations.

![Figure 2: Timbrel masonry vault tested (a) and displacement histories applied to the structure (b).](image)

The behaviour of the vault has been described in terms of: the evolution of the reaction forces in all the supports, (ii) the widening of cracks and the corresponding changes in vault behaviour and (iii) the history of the displacements applied to support S1.
Vertical reactions were obtained averaging the deformations read by three strain gauges (−120°/0°/120°) placed on the steel tubes forming the mechanical support apparatus. Similarly, displacements and strains of the parts of the vault where the cracks are expected to form were monitored by means of: (i) Linear Variable Displacement Transducers (LVDTs) and (ii) Fibre Optic Sensors (FOSs).

Figure 3: Textile Reinforced Mortar (TRM) material applied on the tested vault (a) and displacement histories applied to the structure (b).

As mentioned above, the masonry vault was repaired and strengthened by means of a 10mm thick extrados layer of Textile Reinforced Mortar (TRM) material. The strengthening is composed by a balanced 25 mm spaced glass textile interposed between two 5 mm thick layers of mortar matrix. The repairing of the vault followed three phases: (i) injection of the cracks to restore the original bearing capacity of the masonry support, (ii) application of a first 5 mm thick layer of mortar, (iii) application of the textile network and finally (iv) covering of the glass textile by means of a final 5 mm thick layer of mortar. The configuration of the strengthening applied at the extrados of the vault is visible in Figure 3(a).

2.2 Experimental results

This section is devoted to the discussion of the experimental results obtained at the end of the laboratory campaigns. In Figure 4 are reported the force-displacement curves obtained testing the unreinforced and TRM reinforced masonry vault for all the monitored supports.
Figure 4: Comparison of the experimental results obtained before the strengthening (a) and after the repairing (b).

As clearly visible, the application of the TRM is able to restore the original load-bearing capacity of the masonry vault as well as to improve its behaviour during the soil settlement. As a matter of fact, although the vault during the first phase of the test experienced a damage mechanism involving the formation of a curved hinged crack along the diagonal arch S2-S4, the reinforced vault behaviour is characterized by an initial approximately linear branch from 0 to 10 mm. This finding, together with the increasing of the peak forces experienced during the test, suggest that the TRM material was able to extend the elastic behaviour of the vault as well as to improve its capacity to withstand possible distortions of the supports. It is worth mentioning that the ultimate displacement found testing the unreinforced vault is almost an half with respect to the TRM strengthened case. Figure 5 depicts the failure mechanism observed when testing the unreinforced vault. As it is possible to notice, the crack pattern comprised the formation of a diagonal hinge connecting supports S2 and S4. Similarly, the TRM strengthened structure experienced the formation of damages in the same position. At the end of the test, no detachment of the TRM was observed, neither the tensile rupture of the strengthening.
Figure 5: Comparison of the experimental failure mechanisms obtained at the end of the first test.

3. NUMERICAL ANALYSES

This section is devoted to the discussion of the numerical models carried out to analyse the behaviour of the masonry vault subjected to soil settlement. Also, the effectiveness of TRM strengthening as repairing solution was investigated. To this scope, a tri-dimensional FE model developed by means of the commercial software Abaqus 6.14 [9] was adopted. The FE model is composed of four noded shell elements (S4) reproducing both the lateral arches and the masonry webbing. In Figure 6 is depicted the mesh adopted to perform the numerical simulation of the unreinforced vault. The mesh is composed by a total of 11917 nodes. The simulation was performed reproducing the extrados surface of the masonry vault and assigning to the lateral arches and masonry webbing different thicknesses. The mechanical properties of the masonry assemblage were tuned according to a series of laboratory tests developed to characterize the masonry support and described in detail in [8]. The tensile and compressive behaviour of the masonry substrate were modelled by means of the Concrete Damage Plasticity (CDP) [9] model already implemented into the software. Furthermore, the steel bracing frame placed at the base of the structure was modelled by means of equivalent spring element having the same axial stiffness.

Figure 6: FE model developed considering the unreinforced vault.

A comparison between experimental and numerical results is showed in Figure 7a. Figure 7b depicts the crack pattern obtained at the end of the simulation. As clearly visible, the numerical model is able to capture with accuracy the experimental behaviour of the vault. A slightly higher difference is
encountered with respect to the force-displacement curve observed in supports S2 and S4. This is probably due to the behaviour of the vault, which started to rotate around support S3 and developed an asymmetric behaviour. This kind of behaviour could be justified by the heterogeneity of the materials and the not perfect geometry of the vault. Independently from the asymmetric behaviour of the vault, the crack pattern was characterized by the formation of a diagonal hinge connecting supports S2 and S4. A satisfactory agreement is obtained when comparing the experimental crack pattern with the numerical one, as visible in Figure 7b.

![Figure 7: Comparison between the experimental and numerical results considering the unreinforced masonry vault.](image)

The FE model previously described was also used to analyse the effect of the TRM strengthening on the vault. The new mesh was obtained adding the TRM strips on the extrados of the masonry wall and assuming a perfect bond between the masonry substrate and the TRM material. The mechanical properties of the strengthening were calibrated according to the results obtained by a series of
laboratory investigations performed on the mortar matrix. Elastic properties and tensile strength of the glass grid were assumed equal to the mechanical properties provided by the producer. In general a good agreement was found between experimental and numerical results indicating that the proposed approach represents a quite good balance between accuracy and numerical efficiency. In particular, the model is able to predict the formation of the cracks with a satisfactory level of details.

4. CONCLUSIONS

The paper presents the experimental and numerical results obtained considering an unreinforced and TRM reinforced masonry vault tested at the ICITECH laboratories. From an experimental point of view, the same masonry timbrel vault was tested as built and after the application of one layer of TRM. The application of the reinforcement helped to restore the original load bearing capacity of the structure. Also, stiffness, peak forces and ductility were improved by the application of the strengthening. From a numerical point of view, a simple 3D macroscopic numerical strategy was adopted in the present paper to study the effect of the TRM when applied on curved masonry substrates. As visible from the comparison, the numerical strategy was able to predict the structural behaviour of the unreinforced and repaired vault. Furthermore, a satisfactory agreement was obtained between the crack patterns obtained at failure.

REFERENCES


