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Strengthening masonry vaults with organic and inorganic composites: An experimental approach

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A B S T R A C T

Polymer-reinforced fibers are now commonly applied to buildings for structural retrofitting purposes. These materials add greater tensile strength to structures, at the expense of a slight increase in weight. However, they also have other disadvantages such as brittle behavior and lack of water vapor permeability, which are not desired in the conservation of heritage buildings.

Alternative composite materials embedded in an inorganic matrix are presented, which solve some of the drawbacks associated with organic matrices. Long steel fibers and basalt textiles are applied to the resistant core of the inorganic matrix to produce a steel-basalt reinforced mortar-based composite. Firstly, a mechanical characterization of the individual components and the resulting material was performed. Secondly, non-strengthened and strengthened real-scale (2.98 m span, 1.46 m high and 0.77 m deep) brick masonry vaults were tested up to failure, in order to demonstrate the mechanical effectiveness of these composite materials. Finally, a comparison between two mortar composite materials (steel-strips/basalt-textiles embedded in a polymer matrix) was performed, with the same real-scale brick-vault failure tests.

The experimental campaign demonstrates that the steel/basalt composite mortar is a feasible alternative, which is physically compatible with masonry structures, easy to apply, and effective for the reinforcement of brick vaults.

1. Introduction

Externally bonded (EB) composite materials are fast becoming the standard solution for structural strengthening, substituting traditional techniques (reinforced concrete, steel, etc.) that can shorten the lifespan of the structure and alter its esthetic appearance. Various research works have demonstrated that EB materials find appropriate solutions and perform well when applied to masonry structures that are at severe risk of deterioration and collapse over time [1–3].

Fiber Reinforced Polymers (FRPs) based on unidirectional sheeting embedded in an organic matrix were introduced in the 90s. Over the past two decades, the reinforcement of arches and vaults using FRP materials have provoked great interest and several experimental studies have shown evidence that it is a valid option for strengthening and/or repairing masonry [4–8], particularly, arched masonry structures [9–12]. Setting the most interesting advantages of FRP aside, the results obtained so far may hardly be considered satisfactory in terms of a lack of ductility, sensitivity to high temperatures, cultural incompatibility (surfaces of ancient and stony substrates), etc.

The present research is focused on inorganic matrix composites, i.e. Textile Reinforced Mortar (TRM) and Steel Reinforced Mortar (SRM) [13–15], which offer advantageous solutions due to their water-vapor permeability, applicable over humid substrate (common situation in masonry structures), lack of toxic substance emission in case of fire, fire resistance, ease-of-application, and of removability. Although their mechanical properties in comparison to organic composites can be less effective, and may require longer curing periods (weeks), for example, their overall behavior makes them an attractive solution for the retrofitting of masonry structures [16–18]. TRM and SRM strengthening solutions are designed to preserve existing masonry structures and to prevent brittle failure. For this purpose, constitutive materials of the composite must be appropriately selected.

The effectiveness of EB reinforcement is highly dependent on the bond between the composite and the substrate, and the interaction between the matrix and the inner reinforcement. Interface behavior and the mortar-reinforcement bond are therefore key factors in the performance of the strengthening technique. Hence, the most important characteristics of the matrix should be as follows: adequate consistency to penetrate the textile (dependent on textile density and geometry), workability, chemical and physical compatibility with the substrate, adequate mechanical properties, low creepage and shrinkage, and good fire resistance.

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Bidirectional textiles (TRM) of a different nature (basalt, glass, hemp, etc.) and unidirectional steel fibers (SRM) are both used in the inner reinforcement of the composite. The fiber quantity and the geometrical distribution of the textile, i.e. the spacing of rovings and their direction, can be independently controlled, thereby affecting the mechanical characteristics of the textile and the degree of penetration of the mortar through the mesh openings (cells) [19].

The transmission of effort from matrix to steel cords in SRM is through their adherence between each other. Long steel fibers and basalt textiles are applied to the resistant core of the inorganic matrix to produce a steel-basalt reinforced mortar-based composite. In the case of TRM, bidirectional textiles such us BRM (basalt fibers embedded in the EB matrix) are usually applied, in order to improve bond behavior. Normally, when loads are applied in a single direction, transversal fibers are designed to maintain roving spacing and to improve the bond between textile and matrix. When the main material is too expensive or difficult to mesh, longitudinal fibers are placed onto an orthogonal mesh composed of an adaptable and cheap compound. Fig. 1 presents both cases that are studied in the present paper: cords/strips (made of steel) and basalt textile.

This research work investigates BRM and SRM retrofitting of masonry vaults, among other solutions, which is a novel area of experimental research. Recent studies on the strengthening of arches [20,21] and walls [18] with inorganic-based composites have demonstrated that their structural behavior improves, in terms of ultimate load and displacement. However, very little work has been done on arched structures strengthened with BRM and SRM and further investigation is essential prior to the development of real applications.

2. Objective

Our aim is to contribute to the conservation of the structural integrity of our historical heritage through an in-depth study of a reinforcement system for brick vaults. This study seeks to contribute to expanding our knowledge on the behavior of brick masonry vaults and the effectiveness of a reinforcement system based on basalt textiles and steel cords, embedded in inorganic matrices, known as Basalt and Steel Reinforced Mortar: BRM and SRM, respectively.

The first step was to perform a mechanical characterization of the materials. In a second step, the experimental work on masonry arches (constructed with the same materials and geometry as in real structures) was designed, in order to fulfill the following objectives: to characterize the structural behavior of non-strengthened vaults and to study the influence of the BRM/SRM strengthening system on the behavior of the vaults as it relates to the failure mode, load bearing capacity and deformation. In a final step, vaults strengthened with Basalt and Steel Reinforced Polymer (BRP and SRP, respectively) were tested to perform a structural evaluation and comparison.

As clearly stated by Dr. Valuzzi et al. [2], EB strengthening composite solutions always increase the ultimate strength of masonry structures, but this increased strength is not always accompanied by higher ductility. Therefore, further research should be conducted to assess whether EB composites can prevent brittle collapse. In line with this objective, the novel aspect of this present paper is mainly based on the combination of three main aspects. Firstly, the constituent materials combined in the studied TRM composites. Secondly, the structural evaluation focused on two completely different EB composites (due to their specific matrices): organic (wet lay-up) vs. inorganic (lime mortar). And, thirdly, the experimental approach applied in the tested vaults: masonry type (erected with materials and geometry presented in real cases), structural test lay-out (asymmetric load configuration), and the vault dimensions (full-scale).

The non-strengthened (one case study) and the strengthened (the other case study) vaults are separately considered due to their different characteristics. These two vault types have been discussed in terms of load (initial linear behavior and load-bearing capacity) versus deformability. Further discussion and related experimental work involving analytical and numerical approaches is an area for future research.

3. Material characterization

This section describes the mechanical characterization of the materials found in the brick masonry specimens (component level) and the reinforcement system (composite level).

3.1. Masonry: brick, bedding, and matrix mortar

The vaults were constructed with solid facing "Rosso Vivo — A6R55W" clay bricks (250 × 120 × 55 mm) from San Marco-Terreal (Italy). These soft mud bricks have two different surfaces: one face is rougher and more porous than the other more refined surfaces. In total, 18 bricks — six per test — were used in the material characterization tests. Compressive strength (f_{cm}) tests were based on Standard EN 772–1:2001 [22]. The value of the elastic modulus (E) was calculated in accordance with Standard UNI 6556:1976 [23] while the flexural strength (f_{tm}) was performed following the specifications stated in Standard EN 67042:1988 [24]. These mechanical properties are included in Table 1.

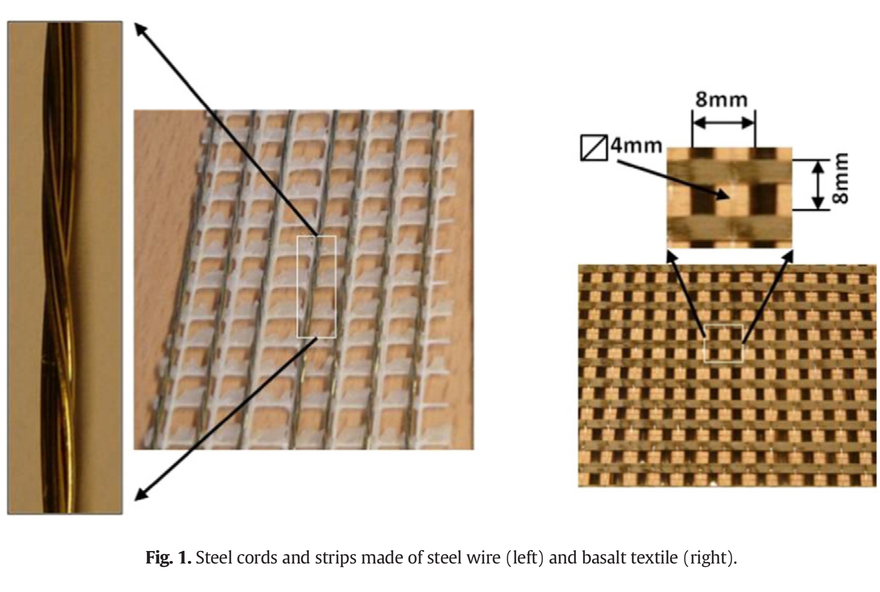

Fig. 1. Steel cords and strips made of steel wire (left) and basalt textile (right).