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Experimental and numerical study on retrofitting of historical masonry vaults by means of fibre-reinforced mortar

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Abstract

Arches and vaults represent important components in historical masonry structures. From the mechanical point of view, they represent the only way to create large openings or horizontal floors without resorting to tension-resisting elements. However, past research and observations of damage after seismic events have highlighted the high vulnerability of such elements under horizontal actions. Moreover, in monuments and historical heritage their intrinsic artistic value is often significant, and thus the need for repairing or retrofitting must compromise with the requirements of compatibility with the old materials present. In this context, the use of lime-based mortar as re-pointing or surface treatment would represent the optimal material, but its low tensile strength and high brittleness make it unsuitable as a retrofitting technique. The introduction of natural or artificial fibres in the mortar paste may remarkably increase the strength and the ductility of the material, making it competitive to other techniques and preferable from the viewpoint of compatibility.

In this research, a retrofitting technology based on the application of fibre-reinforced lime-based mortar (FRLBM) on masonry vaults is investigated. Scaled 1.5m-span arches made of tuff blocks, which represent the most common block material in Southern Italy, are experimentally tested under constant vertical loads and monotonic horizontal forces. The arches are tested in unreinforced and reinforced configuration, consisting of 1-cm thick layer of mortar applied at extrados. The results show a remarkable increment in strength and ductility of the arches as an effect of the FRLBM. Numerical simulations of the retrofitting technique are also developed and allow for the extension of the experimental results to different configurations. Future

improvements of the technique and the materials are envisaged based on the outcomes of the described activities.

Keywords: Masonry vaults, seismic loading, retrofitting, lime-based mortar, fibre-reinforced mortar.

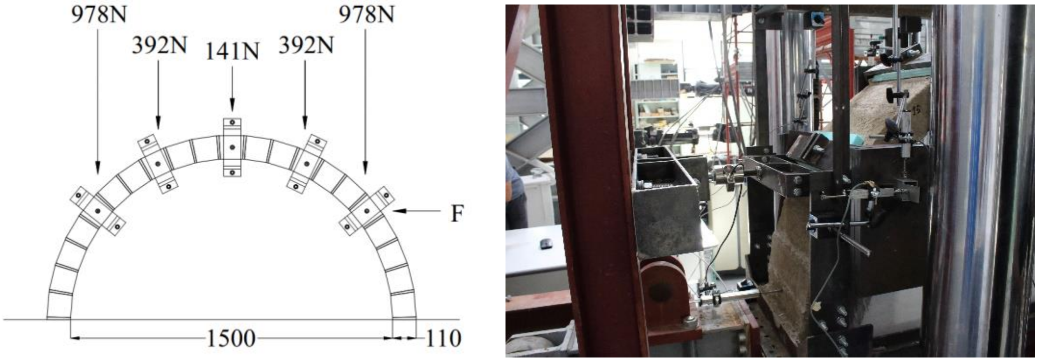
1 Introduction

Masonry structures represent the largest share of built historical heritage and need to be preserved from the effects of anthropic and natural actions as earthquakes. Recent studies on seismic vulnerability have clearly shown that masonry arches and vaults, largely present in churches, monuments, bridges, are among the most vulnerable structural elements [1]. In this context, the main traditional retrofitting techniques used in practice are tie rods or buttresses counteracting the thrust, which produce a significant change in the aesthetics and structural behaviour of the original structure. Other methods as Fibre Reinforced Polymers in the form of sheets or plates have proved very effective in terms of strength increment [2] but do not satisfy compatibility and reversibility prescriptions for heritage structures. In this context, the use of lime-based mortar as re-pointing or surface treatment would represent the optimal material, but its low tensile strength and high brittleness make it unsuitable as a retrofitting technique. The introduction of fibres in the mortar paste has been proposed very recently for retrofitting of masonry walls [3], leading to very promising results. The application of Fibre-Reinforced Lime-Based Mortar (FRLBM) to arches and vaults is conversely yet to be fully explored, to the authors' knowledge. In [4], tests on arches retrofitted by steel fibre-reinforced mortar under concentrated vertical loading were carried out, showing that this type of retrofitting may be so effective to modify the failure mode of the arch from flexural (with the formation of four hinges) to shear.

In this paper, preliminary results from the experimental/numerical programme carried out within the ARCH project (Advanced Retrofitting for Curved Historical structures), funded by the University of Campania "Luigi Vanvitelli", are presented. The aim of the project is to investigate experimentally the mechanical behaviour of scaled barrel vaults retrofitted with FRLBM under horizontal forces and provide indications for the numerical simulation of the system.

2 Methods

The structures tested were two 1.5 m span circular arches with 11 cm thickness and 37 cm width, made of a single layer of 11×10×37 cm^3 yellow tuff blocks. The thickness of the lime mortar used between the blocks was nominally equal to 10 mm. The materials used for the arch construction were selected to resemble historical materials used in Campania region (Southern Italy). The arches were subjected to constant vertical loads simulating the weight transferred by the backfill usually used in vaults, applied on five points symmetrically placed (Figure 1). The loads were simulated by steel plates connected to the arch by means of couples of omega-shaped steel elements enclosing a single block. After the application of the vertical loads, one of the loaded points, approximately as high as the arch barycentre, was horizontally restrained to the external steel frame by means of a device in which a load cell was connected in series. The arch was rigidly connected to a sliding base at the bottom with the possibility of movement with respect to the external frame. In this way, a concentrated force was applied to the loading point.



(a) (b)

Figure 1: Experimental setup for the tests on the arches: (a) drawing, and (b) detail of the restraint.

The FRLBM retrofitting, made of M15 lime-based mortar with short fibres dispersed in the paste, was applied as a 10-mm thick layer at extrados. One of the two specimens was not retrofitted, acting thus as a control specimen.

Experimental tests were performed on materials, small assemblages and arches. Among the others, material tests included:

1. Indirect tensile (bending) tests and compressive tests (EN 1015-11) on M15 fibre-reinforced mortar;
2. Indirect tensile (bending) tests and compressive tests (EN 1015-11) on lime mortar for arches;
3. Indirect tensile (bending) tests (EN 1015-11) and compressive tests (EN 772-1) on tuff stones for arches.

Numerical simulations consisted of limit analysis of the arches, where the reinforcement was considered as a perfectly plastic tie applied at the extrados [5]. The mechanical characteristics of the FRLBM were calibrated against finite element (FE) models. The former analyses were performed by means of a tool specifically developed by the first and last authors [5]. The FE models of the material tests were developed in Code Aster [6]. The material model used was the Double Drucker Prager model with parabolic compression softening and exponential tensile softening [7].

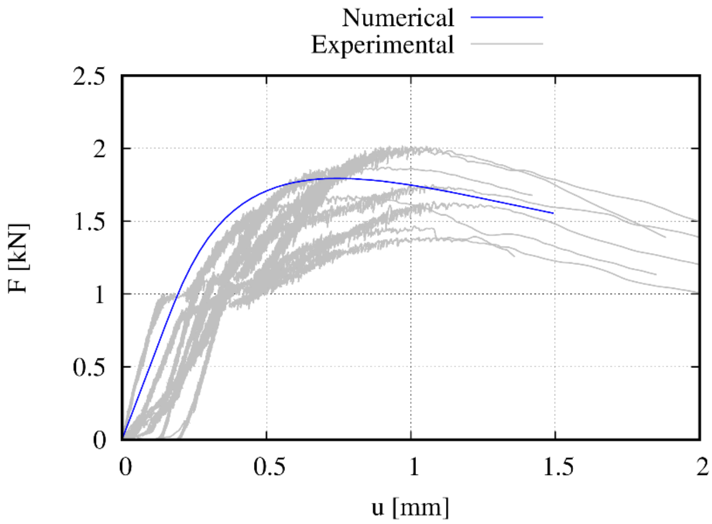
3 Results

The material properties are reported in Table 1. The FRLBM flexural strength was evaluated by means of the equations suggested by EN 1015-11, which are based on elastic stress distribution. However, due to the significant redistribution allowed by the presence of the fibres, this is not equal to the tensile strength of the mortar. Numerical simulations of the flexural test on mortar allowed contemporary calibration of FRLBM tensile strength f_{mt}=1.75 MPa and fracture energy G_t=0.7 N/mm.

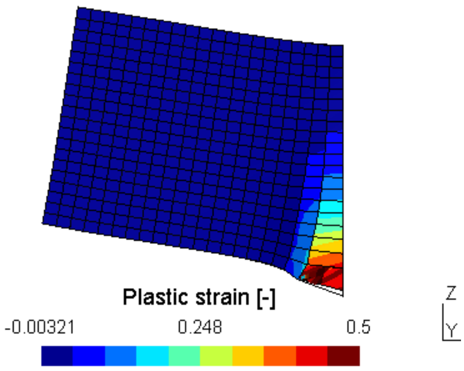
Symmetry was used to decrease the computational demand. A comparison between experimental and numerical curves for the mortar is shown in Figure 2, along with the experimental and numerical view of the specimen at collapse.

Property	**Average**	**CoV**
FRLBM flexural strength [MPa]	4.024	0.127
FRLBM compressive strength [MPa]	20.20	0.032
Lime mortar flexural strength [MPa]	0.490	0.106
Lime mortar compressive strength [MPa]	1.543	0.163
Tuff flexural strength [MPa]	0.824	0.022
Tuff compressive strength [MPa]	2.917	0.257
Tuff density [kg/m^3]	1262	0.020

Table 1: Material properties.



(a)



(b) (c)

Figure 2: Calibration of the numerical model for FRLBM: (a) force-displacement plots, (b) view of a specimen at failure, (c) numerical simulation.

It is possible to notice that, after the flexural crack opening, it is still able to withstand load thanks to the activation of the fibre strength, working even when the crack is significantly opened. This explains the high ductility shown by the material. To make a comparison with normal mortar, the ratio between calibrated G_t and f_{mt} is equal to 0.4 mm in the present case, against the value 0.016 mm suggested for standard lime-based mortar in [8].

After calibrating the mechanical characteristics of the reinforcement, the two tests on the arches were simulated by means of limit analysis. The experimental force-displacement plots of the unreinforced (UR) and reinforced (RE) arches are displayed in Figure 3, together with the predictions given by the numerical tool.

It can be noticed how the peak experimental strengths are well-predicted by the limit analysis. The increase of strength is significant, with the ratio between maximum horizontal force in reinforced and unreinforced conditions equal to 3.13. Furthermore, the ductility shown by the system at collapse in RE configuration, with 20% decrease in strength reached at keystone displacement of 10.1 mm (1.3% drift) highlights the high potential of this retrofitting solution for seismic retrofitting of historical arches and vaults.

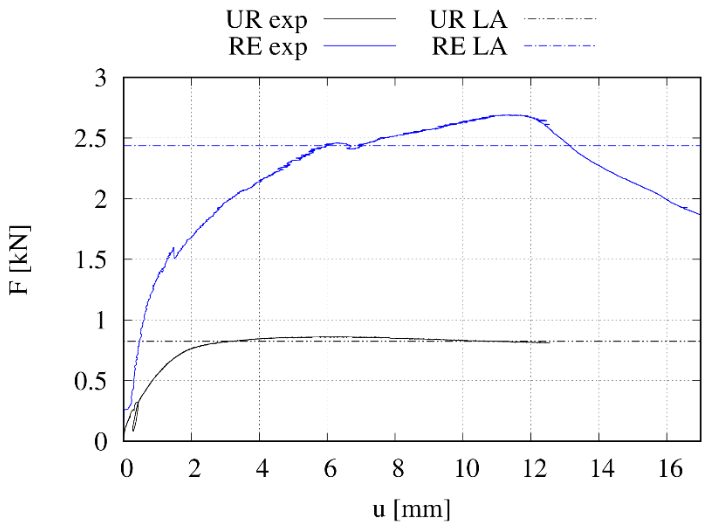


Figure 3: Force-displacement plot of the unreinforced and reinforced arches.

4 Conclusions and Contributions

In this paper, the preliminary results of the ARCH project, aimed at investigating the effectiveness of FRLBM as seismic retrofitting for historical masonry arches and vaults, are described, together with some numerical simulations. Characterisation of FRLBM was performed by standard testing and numerical calibration, showing the remarkable ductility of the material given by the contribution of the fibres after the initiation of cracking. The performance enhancement as retrofitting solution is investigated by a test setup in which a monotonically increasing horizontal displacement is applied at the barycentric position on the arch after applying suitable

vertical loading simulating the load transferred by the above backfill. The preliminary results obtained so far appear very promising, both in terms of strength increase, up to 3.13 times the unreinforced value, and ductility, with drift at 20% strength decrease equal to 1.3%.
Ongoing work is extending the set of experimental results by investigating other retrofitting configurations (intrados/extrados, normal/fibre-reinforced mortar), and parallel numerical simulations will be carried out on the overall structure to parametrically investigate the influence of various mechanical and geometrical parameters.

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