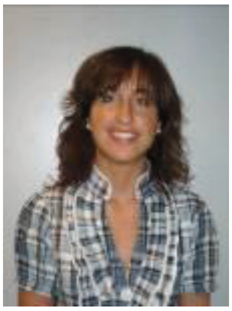
INNOVATIVE COMPOSITE MATERIALS FOR STRENGTHENING MASONRY ARCHES



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ABSTRACT

Masonry arches are part of our cultural heritage. However, the majority of them are deteriorated because they are subjected to different conditions from those that were designed. This paper aims to present an innovative strengthening solution for masonry arches in order to contribute to the maintenance of built heritage; recovering their performance, preventing the brittle collapse and increasing the load capacity of these structures. For this purpose, a compatible and minimally invasive strengthening technique based on Basalt Textile Reinforced Mortar (BTRM) is developed. The experimental campaign consists of the physical and mechanical characterisation of the constitutive materials of the stony structures and the strengthening textile and mortar. Later on, the TRM was characterised as a composite material by means of pure tensile tests. Finally, twelve stone arches were erected, strengthened and tested. The purpose is to compare the mechanical behaviour up to failure of both non-strengthened and strengthened structures varying position of the reinforcement. The experimental results obtained demonstrate good physical-chemical compatibility between the BTRM reinforcement system and strengthening composite material and prove the mechanical effectiveness of the technique.

1. INTRODUCTION

Masonry arches may be found in a large number of buildings and they constitute a fundamental part of architectonic heritage, of immense functional and cultural importance, which are still used nowadays: housing, religious buildings, footways, bridges, aqueducts, and waterways, among others.

A relevant piece of information is that in 1998, a total of 22,827 parish churches were recorded on the national census in Spain. In the specific case of the Spanish state, the national highway grid was 22,500 km long in the year 2000, taking up 80% of the total road traffic. According to the general bridge inventory, arch masonry bridges constitute the 30% of the total number of bridges [8]. In the case of the railways of the Spanish State, almost 45% of their structures are made of masonry [1]. In Europe, the International Union of Railways states that 70% of the masonry structures are between 100 and 150 years old and 12% are even older than that. Furthermore, a great number of the arches that we find today are subjected to conditions different to those for which they were designed.

In general, masonry arches can be damaged due to inadequate design, poor construction practices, changes in their use, ageing effects, poor maintenance, fatigue effects, foundation settlement, earthquakes, architectural changes or load increments. Effective reinforcement restores structural performance, increases load capacity and prevents brittle collapse. As a consequence, it is important to evaluate the structural safety of the building and later, if so required, to design a reinforcement solution.

Effective reinforcement restores structural performance, increases load capacity and prevents brittle collapse. Conversely, reinforcement is also necessary in the cases where the structures must satisfy the requirements of current codes and standards [5]. One of the most important factors in the selection of a reinforcement system depends on its compatibility with the substrate or structure. In this article, Textile Reinforced Mortar (TRM) has been proposed as an alternative to the traditional strengthening techniques as well as to the more traditional Fibre Reinforced Polymers (FRP) [3, 9]. On the one hand, the traditional strengthening techniques can be heavy solutions that increase the rigidity of the original structure and are difficult to be performed. On the other hand, the use of Fibre Reinforced Polymers (FRP) has become popular and worldwide accepted for retrofitting masonry historical structures. It enables masonry structures to bear tensile stresses enhancing their load carrying capacity with minimal addition of dead load [10, 2]. Nevertheless, several constraints associated with FRP should be mentioned: it cannot be applied over humid substrates, it should be applied within a range of temperatures, it cannot resist temperatures over +110ºC÷150ºC, it is prone to brittle collapse and can be incompatible [11] with the parent material (chemical and physical incompatibility, poor flexibility to adjust to building deformations and poor water vapour permeability).

TRM is a composite material that consists of textiles embedded in an organic matrix mortar [6]. As a result, the following advantages can be highlighted: water vapour permeability, ease of application (including on humid substrates), fire resistance, no toxic emissions, adaptability to complex surfaces and low cost. Experimental results showed that glass fibres, which exhibit lower mechanical properties than carbon fibres, strengthened masonry arches more efficiently against collapse mechanisms, and exhibited higher strength and better global ductility [10]. Thus, basalt textiles, which have similar properties to alkali-resistant glass fibres and a much lower cost than carbon or aramid fibres, were applied in this study. As a consequence, Basalt Textile Reinforced Mortar (BTRM) was obtained.

Validation of the proposed strengthening material, BTRM, was assessed by building, strengthening and testing twelve stone masonry arches. The characterisation of constitutive materials and the strengthening composite material is also included.

2. MATERIALS CHARACTERIZATION

2.1 Stone and mortars

Sandstone mortar and poor lime-cement mortar were used for the construction of the arches, because of their availability and similarity with the masonry found in many historic buildings. The composition of the mortar used for setting the voussoirs was adjusted in line with the characteristics of mortars commonly used in ancient masonry structures. The correct proportions were established by gathering data from the specifications of ancient mortars, which were determined at TECNALIA R&I from real life studies.

The type and quality of mortar used in the reinforcement are crucial to the life of a stone building. With regard to the strengthening material, a cement-free mortar is therefore used (Mape-Antique Strutturale). Furthermore, a first coat of a cement-free base mortar (Mape-Antique Rinzaffo) was applied to improve adhesion and add chemical/physical resistance to soluble salts of macro-porous dehumidifying mortars.

With reference to the physical compatibility, the parameters presented in Table 1 were determined by means of mercury porosimetry.

Table 1. Physical analysis of the materials.

Mortar type	Sandstone	Jointing Mortar	MA Rinzaffo	MA Strutturale
Density [Kg/m^3]	2,011	1,625	1,990	1,770
Absorption by capillarity [Kg/m^2 min-$^{1/2}$]	1.48	1.74	0.18	0.36
Absorption under atmospheric pressure [%]	6.5	-	11.69	15.79
Water vapour permeability [Kg/m s Pa]	-	-	2.97E-12	2.07E-12
Porosity [%]	20.4	34.1	26.44	29.92
Average pore size Ø [µm]	28	-	0.05	0.04
Pore size distribution	Unimodal		Bimodal. Average size of 0.75 and 0.04 µm.	Unimodal.

Samples were taken directly during the construction of the arches, stored (20 ºC and HR 60%) and tested for mechanical characterization (see Table 2) in terms of average compressive resistance (f_{cm}), direct tensile resistance (f_{tm}), deformability (E_{cm}), density (ρ) and Poisson coefficient (v) according to standards.

Table 2. Mechanical properties of the constitutive materials

	f_{cm} *[MPa]*	f_{tm} *[MPa]*	E_{cm} *[MPa]*	ρ *[Kg/m^3]*	v
Sandstone	21.3	1.18	5935	2011	0.34
Jointing Mortar	2.03	0.60	5039	1625	0.21
MA Rinzaffo	12.6	1.2	7.2	1910	0.29
MA Strutturale	21.6	2.2	15.7	1770	0.39

2.2 Strengthening material: Textile and BTRM

Basalt fibres have, in general, excellent alkali resistance, similar properties to glass fibres, and considerable lower cost than carbon or aramid fibres. The elastic tensile modulus of basalt fibres (82-110 GPa) is higher than that of E-glass fibres (70-75 GPa) as well as the working temperature range (from -260ºC to 900ºC). Low elongation ratios, and perfectly elastic up to the point of rupture result in fabrics with high levels of dimensional stability that exhibit reasonable suppleness, drape ability, and good resistance to fatigue. Basalt is non-toxic, completely inert and without any environmental restrictions. Furthermore, basalt fibres show excellent "wet ability" (or natural adhesion) to a broad range of binders, coating compounds and matrix materials in composite applications [4]. The manufacturing specifications of basalt textile used in this research are given in Table 3.

Table 3. Manufacturing specifications of the basalt textile used in this research.

Density by area	233 g/m^2
Side length of cell	25 mm
Average thickness: Uniaxial tension	0.0424 mm
Biaxial tension	0.0848 mm

The textile has been characterised in laboratory by means of uniaxial tensile tests, varying the amount of rovings and testing direction. Tensile tests were performed on four different types of specimens: one (TL1) and two (TL2) –yarn specimens, loaded in the longitudinal direction and four-yarn specimens, loaded in the longitudinal (TL4) and transversal (TT4) direction (see Figure 1).

Figure 1. Pure tensile tests of four-yarn basalt textile specimen

On the whole, 40 specimens 400÷500 mm long were tested. The testing machine displacement rate was 5 mm/min. The results obtained are showed in Figure 2. As presented in this figure, the load absorption increases in a linear manner. When the rovings start to break, the load decreases rapidly. It can also be noticed that in the transversal direction, the ultimate strength for 4 rovings is lower than in the longitudinal direction due to the smaller amount of fibres in this direction.

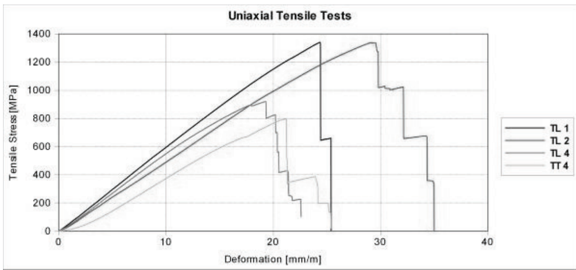

Figure 2. Basalt textile uniaxial tensile tests

With the purpose of analysing the BTRM tensile behaviour, specimens of 100 x10 mm^2 cross-sectional area and 600 mm in length were prepared. They were built with two layers of basalt textile embedded in Mape-Antique Strutturale mortar. The displacement ratio of the test was 0.5mm/min. deformations in the central third part were recorded with four potentiometers. Results are presented in Figure 3.

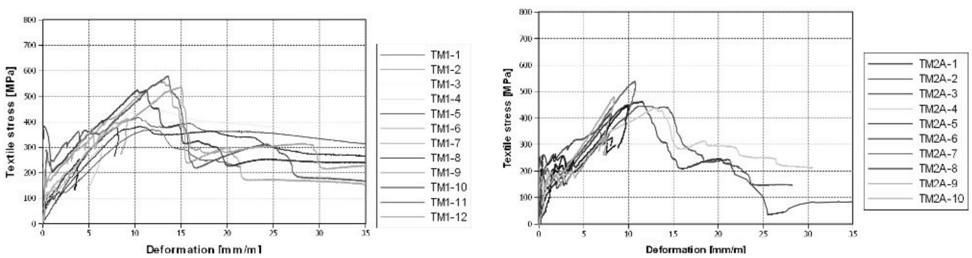

Figure 3. Tensile tests of the BTRM

The stress-strain curve shows three stages. The first stage is very stiff. The curve increases quite rapidly and linearly with a higher Young's modulus than each of the materials that compose the composite. This stage finishes with a loss of load due to the formation of initial cracks. In the second stage, the load increases linearly until the ultimate load is reached. The composite characteristics are mainly influenced by the textile properties. The third and final stage is characterised by the increase in deformation under a constant load.

3. ARCH CONSTRUCTION AND TESTING

To study the effect of the strengthening material twelve stone masonry arches (1.13m span, 0.44m height, 0.25m width, 0.12m thickness) were constructed, strengthened and tested on the TECNALIA R&I platform for structural testing: 3 control arches (A), 3 strengthened on the extrados (EX), 3 on the intrados (IN) and 3 on both sides (EXIN). Specifically, the load was applied at the quarter of the span, distributed along the whole of the upper surface of the voussoir, in order to facilitate the collapse of the structure. The test was carried out up to failure, using displacement control, at a speed of 0.12 mm/min. During the tests, both horizontal and vertical displacements were recorded during the tests using 14 LVDTs.

The reinforcement had a first coat of base mortar layer (Mape-Antique Rinzaffo) on which the matrix mortar was applied (Mape-Antique Strutturale). Two layers of basalt textile were embedded within the mortar. The total thickness of the strengthening was about 15 mm.

4. RESULTS

An arched masonry structure is stable under a given loading condition as long as the thrust line, which represents the internal forces at every cross-section, is kept inside the central core. When the thrust line moves outside the central core, the formation and consequent opening of a crack takes place and a plastic hinge is formed. The appearance of successive hinges forms a mechanism which leads the structure to collapse [7].

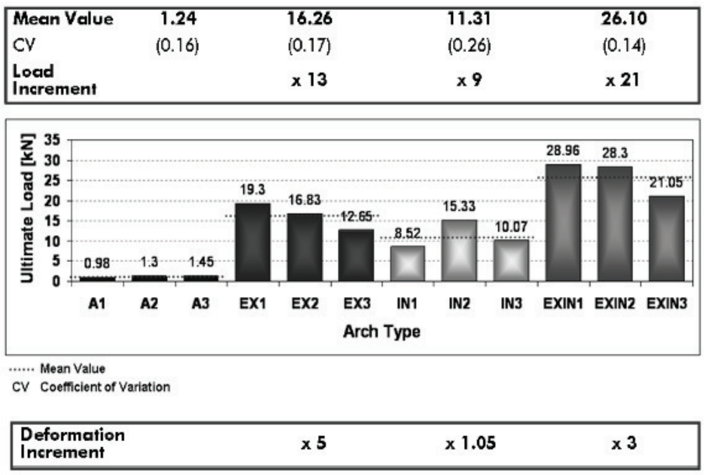

Figure 4. Results of arch testing

In this case, different failure modes were observed. Unstrengthened arches presented an abrupt failure while strengthened arches presented a more ductile behaviour and a higher ultimate load (Figure 4). Furthermore, in the arches that were reinforced on the extrados or the intrados, the formation of plastic hinges was accompanied by other failure mechanisms: separation of the reinforcement and slipping between joints (Figure 5). There is no a unique failure mode for each type of strengthening. In the arches reinforced on both sides, failure of the stony material was reached due to the notorious increase of the ultimate load. It must be considered that tests were performed up to collapse what provoked crushing of the stony material. In real situations, unsafe situations are supposed to be avoided.

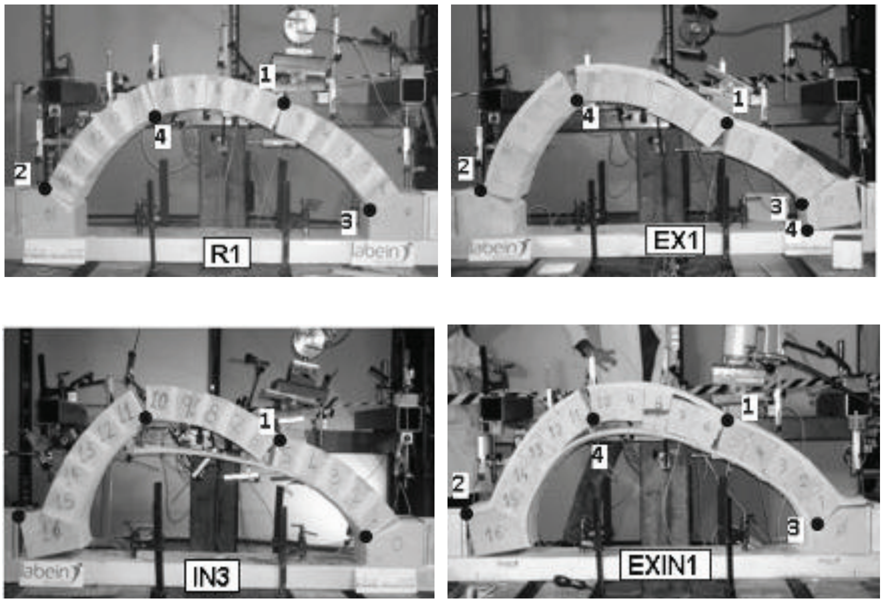

Figure 5. Failure modes and hinge position according to different strengthening lay-outs.

5. CONCLUSIONS

This paper has presented how the BTRM technique is a promising solution for the strengthening of masonry arches. The inorganic matrix of the mortar presents a series of advantages which are very much in accordance with the requirements for restoration of masonry structures. On the one hand, the physical-characterization of the stone used in the construction of the arches and of the reinforcement mortars show that the hydric properties of the reinforcement materials do not harm the stone. On the other hand, the mechanical validation has been assessed by a laboratory test campaign on individual materials (stone, mortars and textiles), TRM and 12 stone masonry arches. It must be underlined that the average gain in ultimate load of arches were 9 times higher than control arches for those strengthened on the intrados, 13 for those strengthened on the extrados and 21 for those strengthened on both sides. The selection of the best arrangement to use will depend on the possibility of being able to execute it (accessibility, aesthetic, etc.) and the desired solution

ACKNOWLEDGEMENTS

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