Advanced Materials Research Vols. 133-134 (2010) pp 849-854
© (2010) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMR.133-134.849

Innovative Strengthening Solution Based on Textile Reinforced Mortar for Stone Masonry Arches

GARMENDIA Leire[1,a], SAN-JOSÉ José-Tomás[1,2,b], GARCÍA David[1,c], LARRINAGA Pello[1,d] and DÍEZ Jesús[1,e]

[1] LABEIN-Tecnalia, Parque Tecnológico de Bizkaia, Bizkaia, Spain

[2] Dept. of Engineering of Materials, University of the Basque Country, Bizkaia, Spain

[a] lgarmendia@labein.es, [b] tomas@labein.es, [c] dgarcia@labein.es, [d] palonso@labein.es, [e]diez@labein.es

Abstract This paper aims to present the design, strengthening and testing of full scale masonry walls and arches. The preservation of our cultural heritage is a really important topic. Majority of masonry structures are deteriorated because of ageing effects, load increments, movements at their foundations, etc. Because of this, retrofitting is needed. In order to afford this problem, a compatible and minimally invasive strengthening technique based on Textile Reinforced Mortar (TRM) is developed. The experimental campaign consists of the characterisation of the constitutive materials of the stone structures and the strengthening textile and mortar (TRM has been characterised by pure tensile tests). Furthermore, the influence of the different arrangements of the masonry and mortar type has been analysed by testing 24 masonry prisms. Finally, 12 full-scale stone arches have been erected, strengthened and tested. The purpose is to compare the mechanical behaviour up to failure of both unstrengthened and strengthened structures. During the tests the effectiveness of the technique has been proved being the ultimate load up to 21 times higher.

Keywords: Stone, masonry, test, arch, strengthening, textile, TRM, TRC

Introduction

A big amount of historical constructions contain masonry arches as part of buildings, railways, waterways and roads. Most of them suffer deterioration because of ageing effects, load increments, etc. Thus, retrofitting is needed and so as to recover their performance. The main goal is to prevent the brittle collapse and increase the load capacity of these structures.

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 (Valluzzi et al. 2001, Basilio 2007). Nevertheless, its application on masonry structures (ACI 2002) presents some critical issues investigated as the compatibility of the FRP system (San-José 2007) with the parent material (chemical and physical compatibility, flexibility to allow building deformations and water vapour permeability). To ensure adequate masonry permeability and comply with restoration requirements, most of the boundary should be left without reinforcement (Foraboschi 2004).

Therefore, one solution is the replacement of the organic matrix with an inorganic mortar. Furthermore, in order to guarantee the adhesion between matrix and core, fibres are replaced by textiles. These textiles, combined with inorganic mortars lead to the composite technology named Textile Reinforced Mortar (TRM). Previous researches have proved that TRM can be used for strengthening heritage masonries where the use of epoxy resins is prohibited (Triantafillou 2005). The use of inorganic matrix has several advantages compare to organic matrix, such as: water-vapour permeability, higher fire resistance, easy application and no toxic emissions.

The specific tenacity (ratio: rupture stress/density) of basalt fibres greatly exceeds that of steel fibres. Basalt is roughly 5% denser than glass. The elastic tensile modulus of basalt fibres (82-110 GPa) is higher than that of E-glass fibres (70-75 GPa). The low elongation, perfectly elastic up until rupture, results in fabrics with high levels of dimensional stability that exhibit reasonable suppleness, drape ability and good fatigue resistance. Basalt fibres show excellent natural adhesion to a broad range of binders, coating compounds and matrix materials in composite applications (Operha 2006-2008). Basalt is non-toxic, completely inert and without any environmental restriction. All of this makes basalt fabrics attractive for the reinforcement of composites and Basalt Textile Reinforced Mortar (BTRM) for strengthening masonry structures. (García 2009)

This paper presents the BTRM as the strengthening technique for stone masonry arches. The validation of the proposed technique is assessed by a laboratory test campaign on individual materials (stone, mortars and textiles), 24 masonry prisms, TRM and full-scale 12 stone masonry arches.

Constitutive Material Characterisation

The different materials that compose the arch (sandstone and mortar) have been characterised in terms of average compressive resistance (R_{cm}), tensile resistance (R_{tm}), deformability (E_m) and density (ρ).

Table 1: Average values for test results

	R_{cm} [MPa]	R_{tm} [MPa]	E_m [MPa]	ρ [Kg/m^3]	v
Sandstone	21,3	1,36	5.935	2.011	0,34
Mortar	2,03	0,98	5.791	1.625	0,21

The European Standards specifies that prism testing method reflects the compressive strength and the modulus of elasticity of the masonry element in cost-effective way and provides a degree of correlation with full-size testing. Because of this, 24 stone masonry prisms specimens of 30-40 mm height, 50mm length and 30mm width, bearing in mind influence of the different arrangements of the masonry and mortar type.

Table 2: Material properties for prism construction

	R_{cm} [MPa]	R_{tm} [MPa]	E_m [MPa]
Ashlar masonry sandstone	40.00	6.28	10468
Rubble masonry sandstone	64.60	5.14	10620
Mortar M1 [1]	2.03	0.98	5791
Mortar M2 [2]	0.33	0.19	24.87
Mortar M3 [2]	0.28	0.13	86.0
Mortar M4 [3]	2.9	0.9	*

* Not characterised

[1] M1, white cement - lime - sand: 2 – 0.5 – 10

[2] M2 and M3, white cement - lime - sand: 1.5 – 0.5 – 19

[3] M4, white cement - lime - sand: 2 – 0.5 – 12

The prisms have been tested at 120 days, under uniaxial compression with load velocity control. Load history and crack developments have been recorded. Young's modulus has been defined in line with the ASTM specification.

Table 3: Results of masonry prism testing

Specimen	f_M' [MPa]	f_M [MPa]	ε_{max} [mm/m]	$E_{[30\%-60\%]}$ [MPa]
Ashlar masonry				
PA-M1-1	3.95	12.01	12.59	1375
PA-M1-2	4.94	10.22	18.03	871
PA-M1-3	4.11	11.66	18.38	1191
PA-M1-4	5.40	16.05	17.59	1727
Average values	4.60	12.48	16.65	1291
PA-M2-5	2.25	8.18	20.80	461
PA-M2-6	2.62	7.85	21.02	504
PA-M2-7	3.92	9.81	25.06	628
PA-M2-8	1.96	9.99	26.85	486
Average values	2.69	8.96	23.43	520
PA-M3-9	2.09	4.54	32.79	151
Average values	2.09	4.54	32.79	151
PA-M4-10 [2]	*	8.16	12.39	1220
PA-M4-11	*	11.25	30.09	458
PA-M4-12	*	10.39	34.29	323
Average values	*	9.93	25.59	667
Rough masonry				
PR-M3-1	*	2.83	43.46	79
PR-M3-2	0.39	1.66	42.38	52
PR-M3-3	0.36	1.10	27.70	49
PR-M3-4	0.36	1.76	37.37	69
Average values	0.37	1.84	37.73	62
Filling mortar				
PM-M3-1	*	0.16	26.48	15
PM-M3-2	0.12	0.20	23.35	16
PM-M3-3	0.13	0.18	13.38	13
PM-M3-4	0.12	0.22	21.40	18
Average values	0.12	0.19	21.15	16
Dry joint ashlar masonry [1]				
PdA	3.20	13.13	25.90	1055
PdA2	1.20	4.71	20.78	246
PdA3	0.31	3.52	22.43	412
PdA4	0.35	7.47	24.25	515
Average values	1.26	7.21	23.34	557

* Non-registered result

[1] Specimens built by non-expert masons

[2] Specimen preloaded 3 times before the final up-to-failure test

f_M': the stress corresponding to the first crack in the stone units.

f_M: ultimate load value.

Strengthening Material Characterisation

The BTRM has been used as strengthening material. It is based on a first coat of a primer pozzolanic mortar (named Mape-Antique Rinzaffo), a second coat of a structural cement-free mortar (named Mape-Antique Strutturale), two layers of basalt textiles embedded and a last coat of the structural mortar. In addition, spike-anchors are used to fix the textile onto the substrate to guarantee the reinforcement's effectiveness.

Figure 1: Strengthening of masonry arch

Mortar. The type and quality of mortars used in the reinforcement are extremely important and crucial for the life of a stone building. For this reason, both types of mortars used are free of cement. Furthermore, the primer has been applied in order to improve the adhesion and add chemical/physical resistance to soluble salts of macro-porous dehumidifying mortars.

Table 4: Average values for test results on strengthening mortars

	R_{cm} *[*MPa*]*	R_{tm} *[*MPa*]*	E_m *[*MPa*]*	ρ *[*Kg/m^3*]*	ν
Mape-Antique Rinzaffo	12.6	1.9	7188	1880	0.29
Mape-Antique Strutturale	21.0	3.5	15650	2060	0.39

Textile. The textile has been characterised by means of uniaxial tensile tests. Each specimen is composed of 4 rovings of 500 mm long. The testing machine displacement rate is 5mm/min.

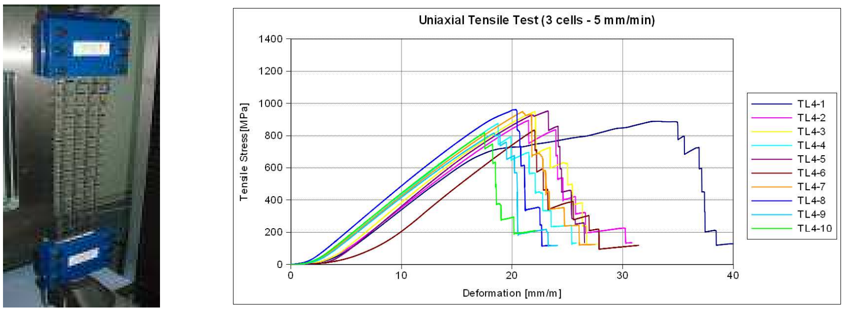

Figure 2: Tensile load tests on ten specimens of basalt fibres

TRM. The TRM has been characterised by means of uniaxial tensile tests. Each one consists of a TRM plate (600 x 100 x 10 mm) with two layers of basalt fabric embedded. The testing machine displacement rate is 5mm/min. The displacement has been measured in the central third part of the specimen.

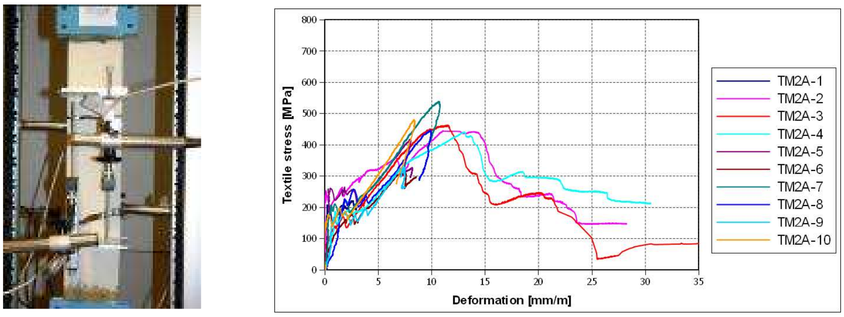

Figure 3: Tensile load tests on TRM.

Stone Masonry Arches

Construction The validation of the strengthening solution is carried out by a laboratory test campaign. 12 stone masonry arches (1.2m span, 0.56m height, 0.25m width) have been built, strengthened and tested: 3 control arches, 3 strengthened at the extrados, 3 at the intrados and 3 at both sides.

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 (Heyman 1966).

The main goal of performed tests is to characterise the structural behaviour of both unstrengthened and strengthened arches and assess the influence of the strengthening on the mechanical behaviour and failure mechanism. Tests have been carried out by displacement control until failure and horizontal and vertical displacements have been registered.

Test Results. Different failure mechanisms have been noticed during the tests. While unstrengthened arches have an abrupt failure when the four hinges are formed, strengthened arches suffer a big deformation before collapse. The arches strengthened at the extrados or intrados collapse due to the formation of four hinges but at higher load values than control specimens. However, other failure modes are noticed: sliding along masonry joint or detachment of the reinforcement. In the case of arches strengthened at both sides, masonry crushing is observed.

Table 5: Average maximum load of stone arches.

Arch	*Average maximum load [*kN*]*
Unstrengthened	1.24
Strengthened at the intrados	11.31
Strengthened at the extrados	16.26
Strengthened at both sides	26.1

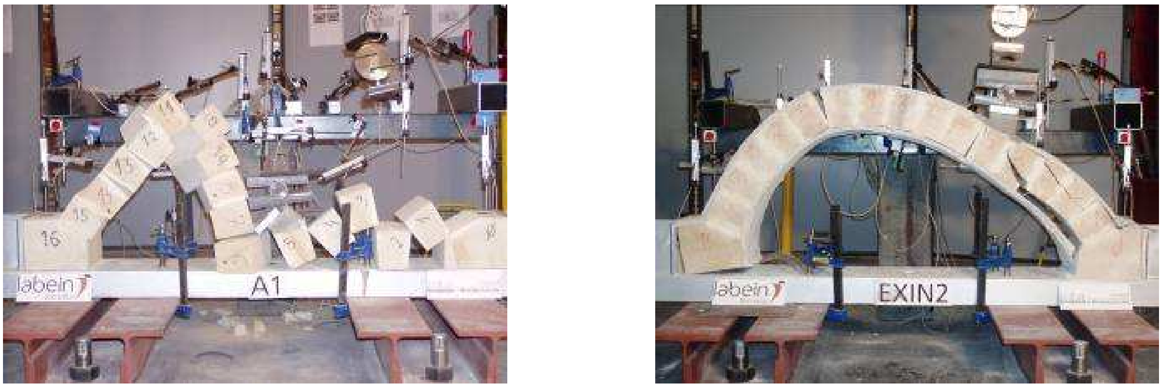

Figure 4: Tests on masonry arches. a) control arch, b) strengthened at both sides

Conclusions

This paper has presented how the BTRM technique is a promising solution for the strengthening of masonry structures: mainly stone masonry arches. The validation of the proposed strengthening technique has been assessed by a laboratory test campaign on individual materials (stone, mortars and textiles), 24 masonry prisms, TRM and full-scale 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 at the intrados, 15 for those strengthened at the extrados and 21 for those strengthened at both sides.

Acknowledgements

This research programme was funded by the Basque Government through the MATE (CTP07-P19), NUCLEO (EMAITEK 2008-2009) and BIRGAITEK (7-12-TK-2009-10) projects.

References

[1] ACI 2002. "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures."- ACI 440.2R-02 P.O. Box 9094, Farmington Hills, Michigan 48333-9094.

[2] Basilio, I (2007). "*Strengthening of arched masonry structures with composite materials*." PhD Thesis, University of Minho, Guimaraes, Portugal.

[3] Foraboschi, P (2004). "Strengthening of masonry arches with Fiber-Reinforced Polymer Strips." *Journal of composites for construction*,8(3), 191-202.

[4] García, D (2009). "*Experimental and numerical analysis of stone masonry walls strengthened with advanced composite materials*." PhD Thesis. Escuela de Ingeniería de Bilbao.

[5] Heyman, J (1966). "The stone skeleton." *International Journal of Solids and Structures*. 2, 249-279.

[6] OPERHA 2006-2008. "Open and fully compatible next generation of strengthening system for the rehabilitation of Mediterranean building heritage" - Contract nº: 517765 (INCO), 6th FP.

[7] San-José, J T, García, D, Garay, A, and Castillo, J (2007). "Novelty FRP strengthening systems applied to different substrates: analysis of the anchorage behaviour," in *FRPRCS-8*. Greece.

[8] Triantafillou, T C, and Papanicolaou, C G (2005). "Textile Reinforced Mortars (TRM) versus Fiber Reinforced Polymers (FRP) as strengthening materials of concrete structures," in *FRPRCS-7*,Kansas City, USA.

[9] Valluzzi, M R, Modena C (2001). "Experimental analysis and modeling of masonry vaults strengthened by FRP," *Int. Seminar on Structural Analysis of Historical Constructions (SAHC-2001)*, Guimaraes (Portugal), 7-9 November 2001, 627-635.

[10] Valluzzi, M R, Valdemarca, M, Modena, C (2001). "Behaviour of brick masonry vaults strengthened by FRP laminates." ASCE *Journal of Composites for Construction*, 5(3), 163-169.