Effect of thermal ageing and salt decay on bond between FRP and masonry

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1 Introduction

The application of FRP systems to historic masonry strengthening and repair is being used even more particularly in seismic areas. FRPs are now preferred to other repair systems as r.c. (reinforced concrete) and steel, since they are light weight and because of their adaptability to complicated shapes [2]. Although a rather great deal of experimental research on the mechanical behaviour of the FRP repaired masonry has been carried out [7], and some standard exists for their application (CNR DT 200 [10], ACI 440 [1]), still some doubt remain on the impact of this technique on the authenticity of the historic buildings. Furthermore, very little experimental work has been done around the world on the durability of these repairs when exposed to aggressive environments (thermal cycles, salt migration, etc.).

The work concerns the experimental characterization of the bond of FRP applied to brick masonry. The collaboration between the University of Padova, the Politecnico di Milano and the Cracow University of Technology in the framework of the RILEM TC MSC "Masonry Strengthening with Composite materials", allowed for a comparison of the performance of various materials, produced in the two countries.

Durability tests, focusing on the influence of temperature variation and salt crystallization were performed. In fact it is know that: (1) detachment of the fibre from the surface can occurs when temperature reaches the "fusion point" of FRP, (2) detachment of FRP can occur when water with salt can entry in the wall. The investigation of these aspects cannot rely upon standardized procedures, and therefore some assumptions were adopted. The study is intended to assess the contribution to bond of both brick and mortar joints. Therefore masonry small assemblages were considered. Only one type of FRP (carbon) was considered, but in different systems (laminate or textile) and with varying properties of adhesives (epoxy resins or polymers), in order to reduce the number of variables.

Masonry specimens were set up as soldier course or running bond specimens, to reproduce bond conditions in thin vaults and in solid walls, respectively.

A procedure for thermal cycles was preliminarily set and then adapted to the characteristic of the specimens. The specimens were inserted in the climatic chamber, with temperature varying from −10 to +70 °C. This temperature range was selected with reference to real life situations. Besides visual inspection, the pull-off testing procedure was chosen as reference test in order to quantify the loss of bond. A total number of 12 specimens were prepared and tested.

It is well known that salt crystallization is one of the most frequent causes of surface damage of masonry in aggressive environments. Therefore, once the repair by FRP is carried out, the presence of salts should not reduce the lifetime of the masonry [4]. Salt crystallization tests on brick masonry assemblages strengthened with FRP strips were performed.

The aim of the research was the analysis of thermal ageing and salt crystallization on bond strength between FRP and masonry substrate.

Comparisons among plain (reference) specimens in normal (environmental) conditions and reinforced ones subjected to aggressive conditions were performed.

2 Material properties

The Italian specimens were made out of two types of solid units: a soft mud and an extruded brick, provided by Sant'Anselmo and Stabila producers, respectively. They simulate units in historic or modern masonry, respectively. The extruded brick was considered as comparison for thermal cycles investigation only. Laboratory tests allowed for the characterisation of the physical and mechanical properties according to EN 771-1 [12], EN 772-1 [23], UNI 8942 [22]. The mortar consisted in a premixed product based on natural hydraulic lime produced by Tassullo (T30V), that provided also its mechanical properties. High-modulus unidirectional textile MBrace Carbon C5-30 was applied with wet-lay-up system, as provided by BASF Italia. Bicomponent epoxy resins used at the interface compose both the primer and the saturant. Properties for fibres and resins (after 7 days of curing, at $T = 20$ °C and RH $= 90$ %) are given by the supplier. For thermal ageing tests, an epoxy resin provided by Fidia producer was also used.

The Polish specimens were made of solid units as extruded bricks provided by Bonarka. Laboratory tests and producers data allowed for the characterisation of the mechanical and physical properties [EN 771-1]. The Polish mortar used is a M5 hydraulic mortar (EN 998-2 [11]) with the addition of trass (Schomburg ASO-TFM-R) for pointing in historical masonry. Three types of CFRP composites were adopted, two laminates and a textile, provided by Sika Poland and applied with wet-lay-up system. Data for the product was provided by the producer. One epoxy resin (Sika Poland) and three types of polyurethane polymers were considered as adhesives. Epoxy resins values were provided by the producer, while polymers were characterized in the laboratory, in accordance to ISO 527 [14].

Mercury porosimetry tests were carried out at Politecnico di Milano on Italian bricks and mortar samples, to measure the total porosity and the median pore radium. The properties of all basic materials are given in Table 1.

Table 1 Properties of materials

Material origin	Brick dimensions (mm)	Brick types	Brick labels	Density (kg/m^3)	Water absorption (%)	Flexural strength (MPa)	Compression strength (MPa)	Splitting tension (MPa)	Pull-off (MPa)	Total porosity (%)	Media pore radium (μm)
Italy	56 × 122 × 255	Soft mud	brI1	1,400	26	4.75	16.51	3.39	1.50	48	0.682
	59 × 112 × 243	Extruded	brI2	1,700	–	4.67	35.36	3.51	3.11	30	0.206
Poland	65 × 120 × 250	Extruded	brP	1,422[a]	20.6[a]	2.09	23.34	–	2.10	–	–

From producer[a]

Material origin	Mortar types	Mortar labels	Flexural strength (MPa, after 28 days of curing)	Compression strength (MPa, after 28 days of curing)	Elastic modulus in compression (MPa)	Total porosity (%)	Media pore radium (μm)
Italy	Hydraulic lime	moI	1.3	3.7	6,130	28	0.348
Poland	Hydraulic lime	moP	1.07	7.0[a]	–	–	–

Mortar joint strength from three-bending test[a]

Material origin	Fibre types	Fibre names	Fibre labels	Tensile strength (MPa)	Elastic modulus in tension (GPa)	Ultimate elongation (%)	Thermal coefficient (1/°C)	Thermal factor (MPa/°C)
Italy	Textile	MBrace C5-30	MB	3,000	390	0.8	1.0E−07	3.90E−02
Poland	Textile	Sika Wrap 230 C/45	W	4,300	238	1.7	3.0E−07	7.14E−02
	Laminate	SikaCarbodur S812	S812	3,100	165	1.7	3.0E−07	4.96E−02
		SikaCarbodur S512	S512	3,100	165	1.7	3.0E−07	4.96E−02

Material origin	Adhesive types	Adhesive names	Adhesive labels	Tensile strength (MPa)	Elastic modulus in compression (MPa)	Elastic modulus in tension (MPa)	Thermal coefficient (1/°C)	Thermal factor (MPa/°C)
Italy	Epoxy resin	MBrace primer	BP	>20	1,900	1,200	6.21E−05	7.45E−02
	Epoxy resin	MBrace saturant	BS	>25	3,100	3,300	6.01E−05	1.98E−01
	Epoxy resin	FidPrimer	FP	45	1,900	2,500	6.21E−05	1.55E−01
	Epoxy resin	FidSaturant HM	FS	70	3,100	2,500	6.01E−05	1.50E−01
Poland	Epoxy resin	Sikadur 30	S30	>26	9,600	12,800	2.60E−05	3.33E−01
	Polyurethane mass	Polymer PM	PM	1.4	–	3.0	1.54E−04	4.62E−04
		Polymer PS	PS	2.2	–	8.0	1.61E−04	1.29E−03
		Polymer PT	PT	18	–	600	1.37E−04	8.22E−02

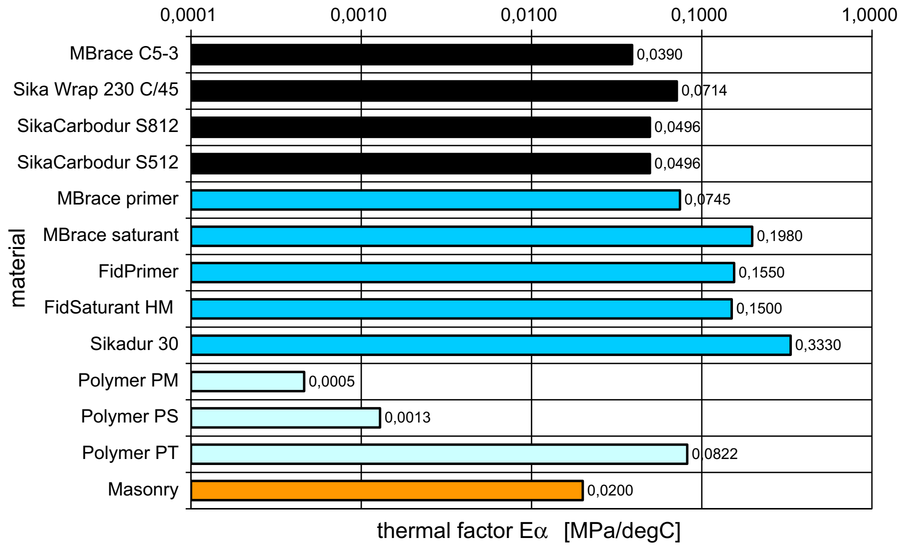

Fig. 1 Comparison of thermal factors $E{\cdot}\alpha$ obtained for the analyzed materials

Increase of uniaxial stress $\Delta\sigma$, caused by increase of temperature ΔT, in perfectly constrained conditions can be computed through the thermal factor $E{\cdot}\alpha$, according to Eq. (1), for any material characterised by the elastic modulus E and thermal expansion coefficient α. More details about values of E and α of materials using in FRP systems in civil engineering can be found in Zając and Kwiecień [27], where values of the thermal factor $E{\cdot}\alpha$ of using strengthening materials are presented (Fig. 1).

$$\Delta\sigma = E \cdot \alpha \cdot \Delta t. \tag{1}$$

The thermal expansion coefficient α for masonry can be considered to be around 5.0E−6 °C and the elastic modulus E for masonry can be considered to be around 4,000 MPa. Following Eq. (1), the thermal factor $E{\cdot}\alpha$ for the assumed masonry can be considered to be around 2.0E−2 MPa/°C. The comparison of calculated thermal factors presented in Fig. 1 in logarithmic scale for analysed materials indicates that change of temperature generates various levels of uniaxial stress σ in materials bonded together (masonry, adhesive layer, CFRP strengthening)—proportional to elongation. If the assumption that the deformation in bond between two compound materials (CFRP-adhesive and adhesive-masonry) can be neglected is valid, there exists shear stress at the boundary. Shear stress is proportional to the difference in uniaxial stress σ in bonded materials.

This shear stress generates tensile stress in the material which has lower value of the thermal factor $E{\cdot}\alpha$ (Fig. 1). If two integrated materials are of high tensile strength (CFRP and epoxy), even high shear stress can be carried. If one of them is weaker and undergoes high shear stress (masonry integrated with epoxy), generated high tensile stress causes failure in weaker material.

A high level of shear stress it is observed when CFRP is bonded to masonry using epoxy resin, especially if the temperature gradient is high. In such a case, failure can occur in material of lower strength, typically in brick.

On the contrary, the use of polyurethane adhesives characterized by low thermal factors indicates that high tensile stress is generated in flexible adhesives by CFRP and masonry (Fig. 1). However, this stress is reduced and uniformly distributed along the whole bonding surface, because of low stiffness and high deformability of flexible adhesives [17]. It should be pointed that not equal value of the thermal expansion coefficient α of integrated materials is valid but the most important is the thermal factor $E{\cdot}\alpha$ from the mechanical compatibility point of view, where also Young's modulus is taken into consideration.

3 Specimen description

All the specimens were reinforced by CFRP, applied as strips of various widths and various types of adhesives. The composite covers also mortar joints, in order to assess the influence of this element on the specimens.

The specimens were prepared at the University of Padova and at the Technical University of Cracow, while all tests (thermal ageing and crystallization tests) were performed at the Politecnico di Milano. The CFRP composite was applied with a classic wet-lay-up method after 1 month of curing of the masonry specimens, thus making sure they were perfectly dry.

Two series of specimens were prepared, simulating various bond configurations, and representative of common brick masonry textures of vaults and walls (Figs. 3, 4). Pilot unreinforced specimens were considered too, as reference for both thermal ageing and crystallization tests in order to evaluate the influence of FRP strips under crystallisation. Joints (for both mortar and polymer) were 1 cm thick; dimensions of the FRP strips varied according to the configuration. However, for single bricks or soldier course specimens, fibres were distributed in an area of 8×21 or 5×21 cm^2 for specimens realized in Italy or Poland, respectively, or on the whole surface (25×25 cm^2); for running bond specimens, the area for each strip was 8×18.5 cm^2 (Italian specimens only).

For thermal ageing tests, three configurations of strengthening were adopted (Fig. 2): one strip on a

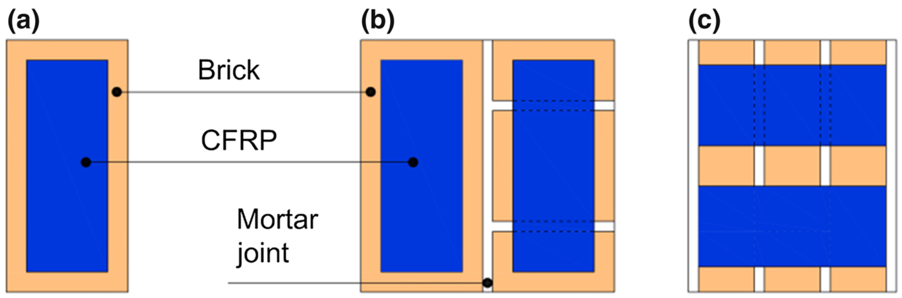

Fig. 2 Configurations of specimens for thermal ageing tests: **a** TA-B: single brick, **b** TA-SC: soldier course specimen, and **c** TA-RB: running bond specimen

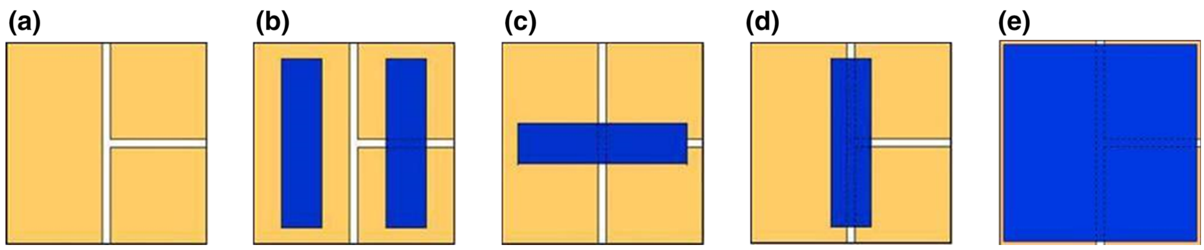

Fig. 3 Configurations for soldier course specimens for crystallisation tests: **a** CR-SC0: plain sample (only brickwork), **b** CR-SC1: two strips combining brick and mortar joint, **c** CR-SC2: one strip with partial covering of mortar joint, **d** CR-SC3: one strip with total covering of mortar joint, and **e** CR-SC4: composite covering the whole surface of the specimen

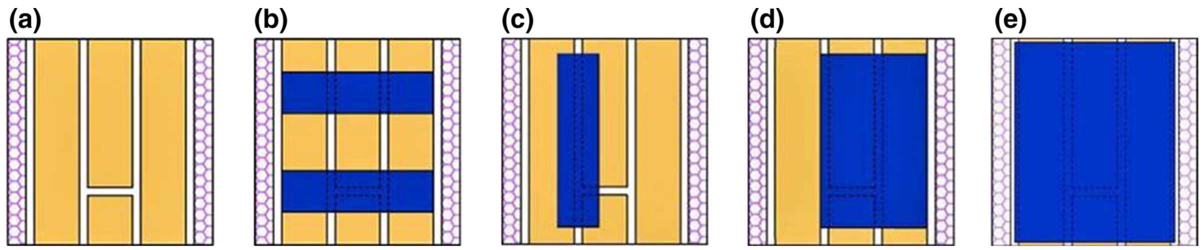

Fig. 4 Configurations for running bond specimens for crystallisation tests: **a** CR-RB0: plain sample (only brickwork), **b** CR-RB1: two transverse strips combining brick and mortar joint, **c** CR-RB2: one strip with total covering of mortar joint, **d** CR-RB3: one strip covering two mortar joints and two bricks, and **e** CR-RB4: composite covering the whole surface of the specimen

single brick, or two strips on soldier or running bond specimens.

For crystallization tests, the strips were applied on each type of specimen according to four configurations (Figs. 3, 4).

4 Experimental program and testing procedures

Tables 2, 3 and 4 present the experimental program of the thermal ageing and crystallization tests. The Polish bricks were used for soldier course specimens

Table 2 Experimental program for thermal ageing tests

Origin	Type of specimen	Specimen labels	Type of reinforcement configuration	Type of brick	Type of mortar	Type of fibre	Type of adhesive	Width of fibre strip (cm)	N. of pull-off for specimen (brick)	N. of pull-off for specimen (mortar joint)
Italy	Single brick	B01	TA-B	brI1	moI	MB	BP + BS	8	0	0
		FF2		brI1			FP + FS		2	0
		EF1		brI2			FP + FS		2	0
		EB2		brI2			BP + BS		2	0
		FB2		brI1			BP + BS		1	0
	Soldier course	SB01	TA-SC	brI1	moI	MB	BP + BS	8	0	0
	Running bond	TB01	TA-RB	brI1	moI	MB	BP + BS	8	0	0
		2					BP + BS		0	0
		3					FP + FS		0	0
		2b					BP + BS		0	0
		3b					FP + FS		0	0
Poland	Soldier course	AG_8_S30	TA-SC	brP	moP	S812	S30	8	3	1
		AG_8_PM					PM		3	1
		AG_8_PT					PT		3	1
		AG_8_PS					PS		3	1

Table 3 Experimental program for crystallization tests

Origin	Type of specimen	Specimen labels	Type of reinforcement configuration	Type of brick	Type of mortar	Type of fibre	Type of adhesive	Width of fibre strip (cm)	N. of pull-off (brick)	N. of pull-off (mortar joint)
Italy	Soldier course	S2	CR-SC1	brI1	moI	MB	BP + BS	8	5	1
		S3	CR-SC2						0	0
		S4	CR-SC3						0	3
		S5	CR-SC4						5	1
	Running bond	T2	CR-RB1	brI1	moI	MB	BP + BS	8	0	4
		T3	CR-RB2						0	0
		T4	CR-RB3						2	2
		T5	CR-RB4						0	4
Poland	Soldier course	CR_PM	CR-SC0	brP	PM	–	–	–	5	1
		CR_M			moP				5	1
		CR_5_PM	CR-SC1			S512	PM	5	5	1
		CR_5_PS					PS		5	1
		CR_25_PM	CR-SC4			W	PM	25	5	1
		CR_25_PS					PS		5	1

Table 4 Experimental program for pull-off tests without thermal ageing and crystallization tests

Origin	Type of specimen	Specimen labels	Type of reinforcement configuration	Type of brick	Type of mortar	Type of fibre	Type of adhesive	Width of fibre strip (cm)	N. of pull-off (brick)	N. of pull-off (mortar joint)
Italy	Soldier course	S1	CR-SC1	brI1	moI	MB	BP + BS	8	2	1
	Running bond	T1	CR-RB1	brI1	moI	MB	BP + BS	8	4	0

only, both for thermal ageing and crystallization tests.

As for thermal ageing, two types of Italian bricks were considered; they were reinforced with a CFRP textile, applied with two types of epoxy resins.

The Polish bricks were reinforced with one type of fiber (laminate S812) 8 cm wide, applied with four types of adhesives (S30, PM, PT and PS). For each configuration one specimen was tested, for both Italian and Polish bricks.

For crystallization tests, Italian soft mud bricks were considered, and only one type of fibre (MBrace) was applied, in four lay-outs. Polish bricks were reinforced with two types of fibres (laminate S512 and textile W) covering part of the bricks (strips of 5 cm for S512) or the whole surface (textile W), applied with two types of adhesives (PM and PS). Moreover two unreinforced specimens were prepared, one with head joints filled by the same mortar as for the reinforced ones, whilst the other using polymer PM. For each configuration one specimen was tested, for both Italian and Polish bricks.

One soldier course and one running bond reinforced specimen (S1 and T1 labelled) were used as reference for both thermal ageing and crystallization tests; two pull-off tests were performed on the brick and one on the mortar joint for specimen S1, four pull-off tests were performed on the mortar joint for specimen T1. The small number of specimens was decided upon, since the research developed is an initial phase intended to test the reliability of the program.

In Table 2 all the thermal tests carried out are reported. In some cases the specimens were not subjected to pull-off, due to their bad condition after the thermal test (value 0) or they were not tested (empty space). The samples exposed to crystallisation cycles are listed in Table 3. In some cases the pull-off strength tests were not carried out, since after crystallisation cycles the samples were extensively damaged (value 0).

4.1 Description of the procedure for thermal ageing tests

In the absence of a standardised method, both the test program and the procedure were proposed according to other previous experiences, basically thermal cycles carried out in the presence of epoxy resin injections [5], also taking into consideration the typical temperatures measured on façades exposed to sun in summer which can even reach 70 °C.

The following procedure was set out in the experimental programme:

(1) Preliminary control of moisture level in the specimen, that should be lower than 12 %, with the specimen cured in a controlled environment (20 °C and 50 % RH) for 24 h.
(2) Execution of the artificial ageing (at 60 % RH) with the following cycles:
    (a) +20 to +70 °C in 1 h (0.8 °C/min),
    (b) 3 h at 70 °C,
    (c) +70 to −10 °C in 1:30 h (1.0 °C/min),
    (d) 3 h at −10 °C,
    (e) −10 to +70 °C in 1:30 h (1.0 °C/min).

Preliminary results [25] obtained on strengthened specimens composed by soft mud bricks indicated a deep delamination of the composite, involving the portion of the brick impregnated by resin. Therefore, to allow for the detection of the commencement of the delamination phenomena, intermediate inspections were carried out every two cycles, these consisted of the following: (a) visual inspection, (b) photographic survey, and (c) description of the observed damage. Forty cycles were performed according to the procedure mentioned above. Then following that stage, pull-off tests were carried out on surviving specimens.

4.2 Description of the procedure for crystallization tests

Crystallization tests were carried out according to the Recommendation RILEM MS A.1 [20]. The specimens, were put in contact with their bottom side with a 10 % (*w*%) Na_2SO_4 solution (anhydrous Na_2SO_4 reagent grade, Fluka) at the bottom end of the specimens and then stored over a layer of dry gravel in a plastic container open at the top, sealed along the borders with the upper face exposed to the environment (controlled laboratory environment of 20 °C and 50 % RH). Due to the fact that the water introduced can evaporate, hence stopping the phenomenon, water was added every 4 weeks, setting up a cycle of water feeding in order to increase the aggressivity of the salt crystallization.

Every 4 weeks the specimen were subjected to: (a) visual inspection, (b) photographic survey, (c) cleaning from efflorescence and detached materials with a soft brush and a vacuum cleaner, (d) photographic survey, (e) description of the observed damage, and (f) reading of the surface profiles by means of a laser profilometer to quantify the damage [6].

Then, after each cycle of 4 weeks, de-mineralised water was added again to restart the process of degradation which can be reduced by the water evaporation.

Eleven cycles were performed according to the procedure mentioned above. Then pull-off tests were carried out on surviving specimens to measure the remaining strength.

Damage induced by salt crystallisation to the substrate and to the bond between CFRP and the masonry in order to predict the effectiveness of the bond adhesion in “real” environmental conditions. Some hypotheses had to be verified: (i) the presence of the stiff and waterproof strips could induce higher damages into the surrounding masonry, and (ii) crypto-efflorescence could be formed underneath the strips and bring to the delamination of the strip itself. The decay mechanisms induced by the salts crystallising into the pores are influenced not only by the porosity characteristics, but also by the pore distribution which varies from material to material.

The test simulated an aggressive environment in which salts can arrive into the masonry by capillary rise. A total number of 16 specimens were prepared and tested.

4.3 Description of the procedure for pull-off tests

The pull-off test is considered as a simple and direct way of quantifying the effectiveness of bond between reinforcement and substrate. Although results can be used directly to calibrate analytical formulations in limited cases (as for detachment of fibres applied at the intrados of vaults [8, 24], since for the majority of applications in building materials (e.g., walls, extrados reinforcement on vaults) is the shear component which is involved in the bond phenomenon [26], pull-off tests constitute a common method for the preliminary characterization of bond. Moreover, the procedure is standardized in ASTM C1583 [3] and be easily performed both in laboratory and in situ. The observation of the failure mode (type A, B, C or D) and the measure of the stress of detachment, provide qualitative and quantitative information on the composite-to-substrate bond. Four types of failure modes are presented in ASTM C1583 [3].

5 Results of thermal cycles tests

The number of thermal cycles applied amounted to 40 cycles and caused a deep delamination in the case of the Italian soft mud bricks. The delaminated layer was trimmed and the section was observed under the stereomicroscope (Fig. 5).

The different layers of FRP, as well as the zone in the brick impregnated by the primer and the resin are presented in Fig. 6a. The figure also shows the delaminated layer with a clear horizontal crack of 1 or 2 cm under the fiber. There was a clear penetration of the primer into the brick (1–2 mm), as it is clear that the impregnated brick is more compact and probably stronger.

On the contrary, the deeper zone which has not been impregnated remained porous and weak. The delamination was observed to have occured at this point. The contact angle test confirms the penetration zone of the primer (Fig. 6b). The reason why this phenomenon happened can be connected with differences between

Fig. 5 Damage observed in the specimens after 40 thermal cycles; detail of the trimmed section

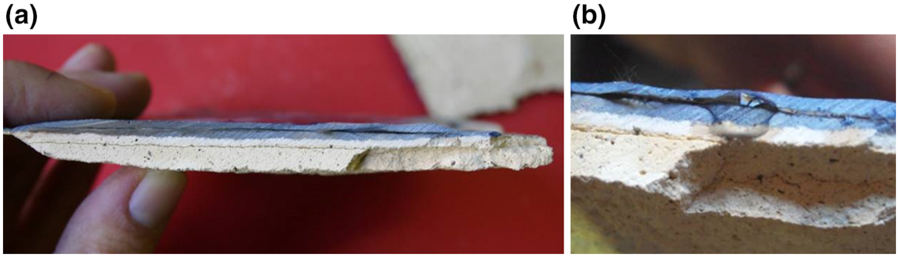

Fig. 6 Visual inspection: **a** delamination on the porous brick after 40 thermal cycles, and **b** presence of a *border* below the fibers at the limit of the impregnated layer

the thermal factors of the soft mud brick and that of the layer of epoxy penetrated into the brick (thin layer of the brick impregnated by the primer). In such a case, the brick of low strength does not withstand the shear stress level causing failure, generated by different deformation of both layers. In real applications on masonry structures exposed to sunlight, the CFRP strengthening system reaches high temperature faster than the masonry substrate, thus the temperature gradient between both materials is higher, generating bigger differences in deformation as presented in Fig. 1.

Four single brick specimens were used, two belonging to the same type of bricks used for the Italian masonry specimens: (a) soft mud ones, characterized by high porosity, and (b) extruded type, characterized by a low porosity. The porous brick suffered delamination after only one cycle, while the five extruded bricks did not have any delamination after all the 40 cycles. The same behavior was observed in the case of the Polish specimens. This confirms that extruded bricks of higher strength were able to withstand shear stress generated by thermal deformations.

6 Results of salt crystallization tests

The results indicate the rising of the salt from the uncovered surface as from the first week of observation, and also a concentration of stresses underneath the fibres [6]. The damage by the salt crystallisation is due to the fatigue caused to the material by the repeated cycles. This measurement is possible because the decay due to salt crystallisation in these porous materials is proceeding from the external surface inward [9].

Furthermore; in these cases it seems that a different damage is induced by the presence of FRP which are partially covering the specimen on the upper surface. Figure 7 indicates that salts are concentrated at the interface between the brick and the fibre, in the zone where most damage occurs due to microcracking.

7 Pull off tests results and discussion

The results of the pull-off tests obtained on specimens subjected to thermal ageing tests are shown in Figs. 9, 10 and 11.

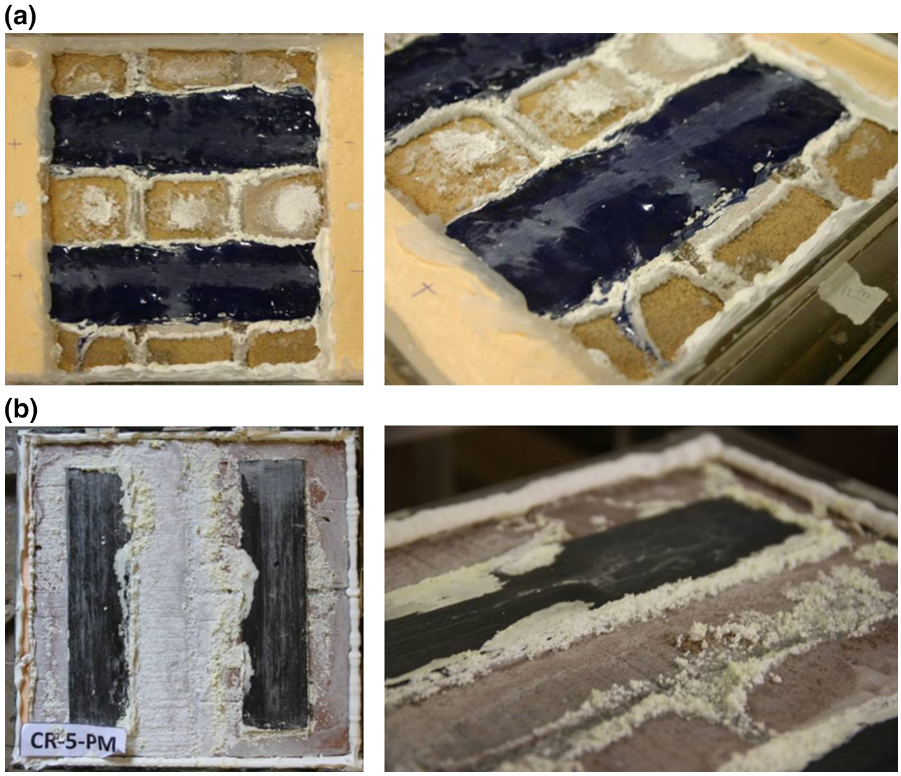

Fig. 7 Damage after 11 cycles of crystallization: **a** general view and detail of concentration of stresses underneath the fibres in Italian specimens, and **b** general view and detail of concentration of stresses underneath the fibres in Polish specimens

On the delaminated brick and on the non-damaged five ones, some preliminary pull-off tests were performed after the thermal cycles and compared with reference pull-off test results, obtained on specimens conditioned in the room temperature. For Polish specimens detailed reference results are presented in [16], where mean values of pull-off tests, obtained for the S30, PT, PS and PM adhesives on Polish Bonarka bricks, were 1.99, 2.34, 1.48 and 0.63 MPa, respectively. For Italian bricks mean values of pull-off reference tests are 1.50 and 3.11 MPa for the soft mud and the extruded bricks, respectively [18, 19].

Results presented in Fig. 11 indicate that in the case of Polish bricks the applied thermal ageing caused pull-off strength reduction: of about 18 % up to value 1.62 MPa for epoxy S30 adhesive, of about 30 % up to value 1.63 MPa for polymer PT adhesive, of about 31 % up to value 1.01 MPa for polymer PS adhesive and pull-off strength increase of about 9 % up to value 0.69 MPa for polymer PM adhesive. In the case of Italian bricks with epoxy adhesive the reduction was: very high 89 % up to value 0.17 MPa for soft mud bricks and very low 5 % up to value 2.96 MPa for extruded ones.

One has to be careful in the analysing of the pull-off results after thermal ageing cycles, particularly in the interpretation of relatively good results (pull-off strength higher than 1.0 MPa) obtained especially for epoxy adhesives. This kind of material loses its properties (starts to be soft) in the temperature range 40–80 °C (Fig. 8), close to the characteristic glass transition temperature T_g, depending of the particular kind of epoxy resin used (producer data). This aspect is very important if strengthening systems are loaded [15, 21]. The presented pull-off test results indicate only the response of the tested strengthening systems surviving after the thermal ageing cyclic process. It cannot be assumed that the obtained in laboratory tests post thermal ageing strength will be the same on the system applied on a real structure, because epoxy resins recover their properties, when temperature goes back under the softening temperature range. In real

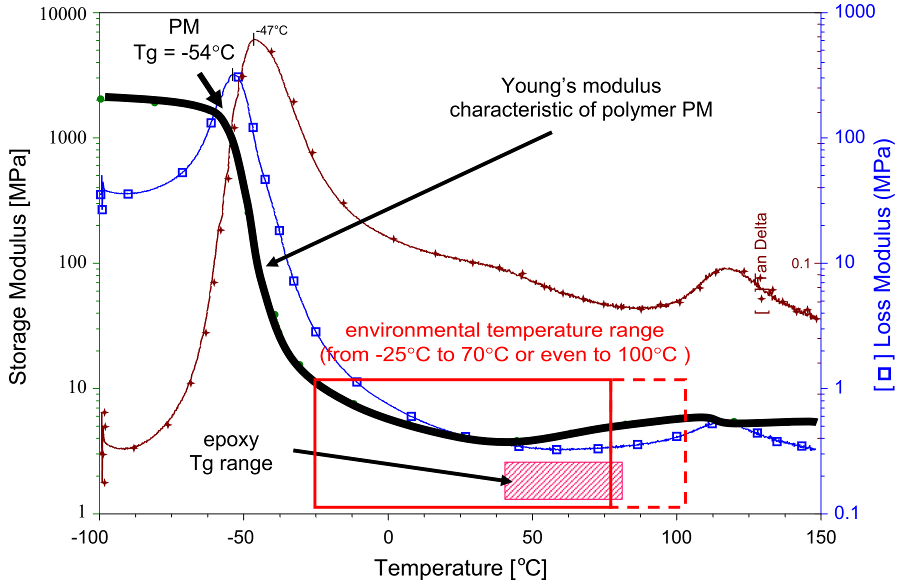

Fig. 8 DMA results for polymer PM performed at excitation frequency of 1 Hz

application, epoxy adhesives (fastening fibres to structures) work under loading, thus, loos of bonding properties of epoxy in the temperatures close to the characteristic glass transition temperature T_g, results in failure of the working strengthening system—there is not any post thermal ageing strength anyway.

On the other hand, polyurethane adhesives (polymers PM, PS, PT) work in the environmental temperature range (−25 to +70 °C or even to +100 °C—Fig. 8) beyond their characteristic glass transition temperature T_g, and are therefore safer in practical applications, when considering thermal aspects. An example dynamic mechanical analysis (DMA) results, for the polymer PM—[13], confirms that this polyurethane works in stable conditions beyond $T_g = -50$ °C in the environmental temperature range (visible in Fig. 8, presenting characteristic of Young's modulus, also named "storage modulus", in the wide temperature range).

The results of the pull-off tests obtained on specimens subjected to crystallisation cycles are shown in Figs. 9, 10 and 11. The reference pull-off test results on brick specimens (without fibres) are represented by mean values 2.10 MPa for the Polish brick [16] and 1.14 MPa for Italian soft mud brick (S1 type) and 0.92 MPa for Italian extruded brick (T1 type).

In the case of Polish specimens (only brick—Fig. 11), the crystallisation cycles led to reduction of about 18 % up to value 1.71 MPa for CR_M and of about 9 % up to value 1.91 MPa for CR_PM. The same crystallisation cycles affected specimens with fibres—Fig. 11. Obtained results (according to references presented for the thermal ageing test) were as follows: about 14 % reduction up to value 0.54 MPa for CR_5_PM, about 6 % increase up to value 0.69 MPa for CR_25_PM, about 61 % reduction up to value 0.58 MPa for CR_5_PS and about 3 % reduction up to value 1.43 MPa for CR_25_PS.

In the case of Italian specimens (with fibres—Fig. 11), the crystallisation cycles resulted in: about 15 % reduction up to value 0.96 MPa for S2, about 15 % reduction up to value 0.96 MPa for S4, about 5 % reduction up to value 1.08 MPa for S5, about 23 % increase up to value 1.13 MPa for T2, about 3 % reduction up to value 0.89 MPa for T4 and about 6 % reduction up to value 0.86 MPa for T5.

The obtained results (compared with reference) indicate that no significant reduction in strength was observed (except CR_5_PS) but even small increase of strength was noticed (CR_25_PM, T2). It is noted that there is a reduction in strength in some cases, this cannot be considered to be the rule after crystallisation. Other factors which can possibly have influenced the discrepancy in results have been observed, such as the presence of the mortar joint, the strength of the brick, the failure mechanisms. Taking into consideration mortar present, it was noted that in some cases

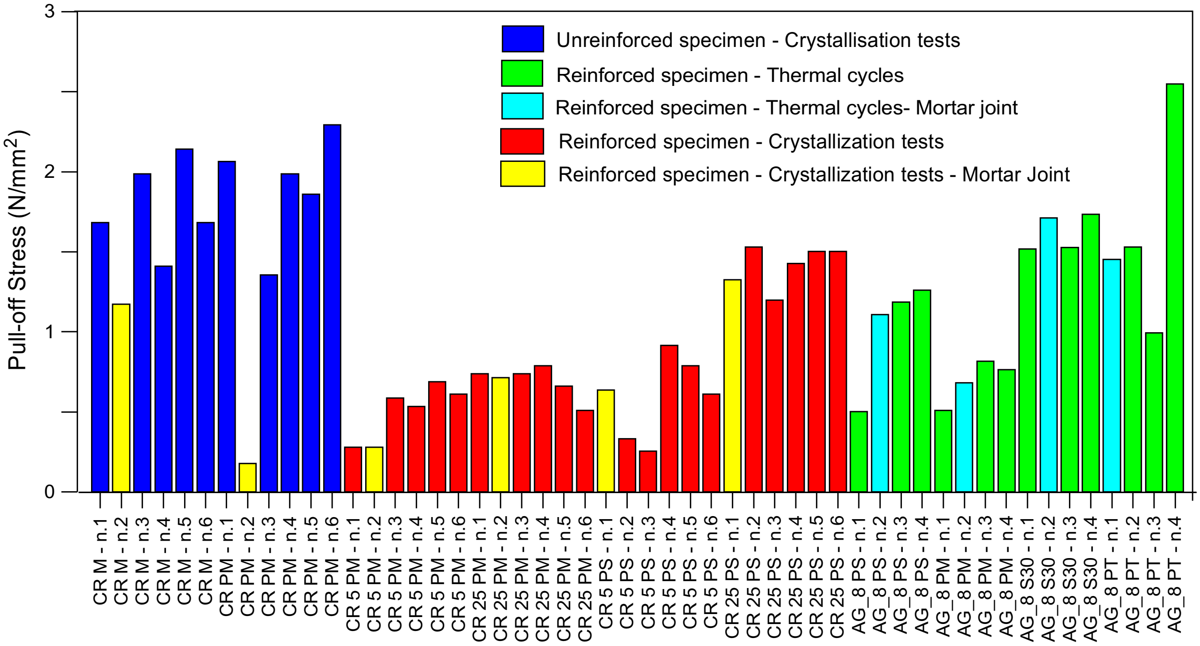

Fig. 9 Results result of pull-off test after crystallization and thermal tests for Polish specimens

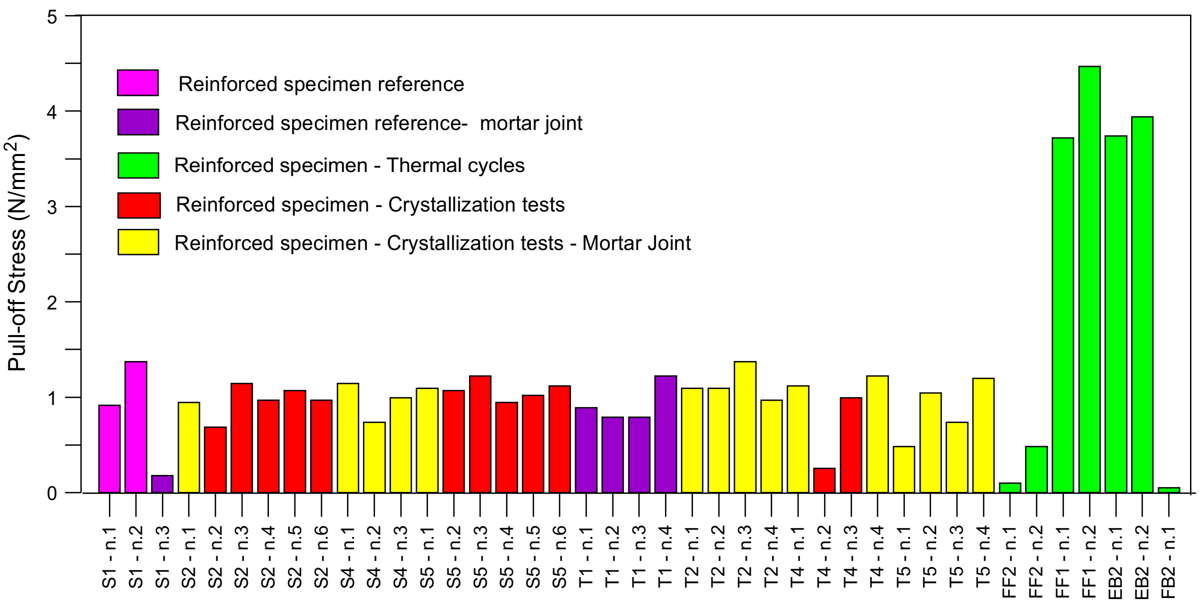

Fig. 10 Result of pull-off test after crystallization and thermal tests for Italian specimens

the strength at failure was reduced drastically, whilst in other cases, the strength was quite similar to the test carried out for the brick only without mortar joint.

The pull-off results for tests carried out on the Italian samples indicate that there is no apparent drastic reduction in strength. Yet one can note the way in which the failure mechanisms vary, with respect to the Polish samples. As discussed above, this depends on the use of different bricks and different materials for the application of fibres.

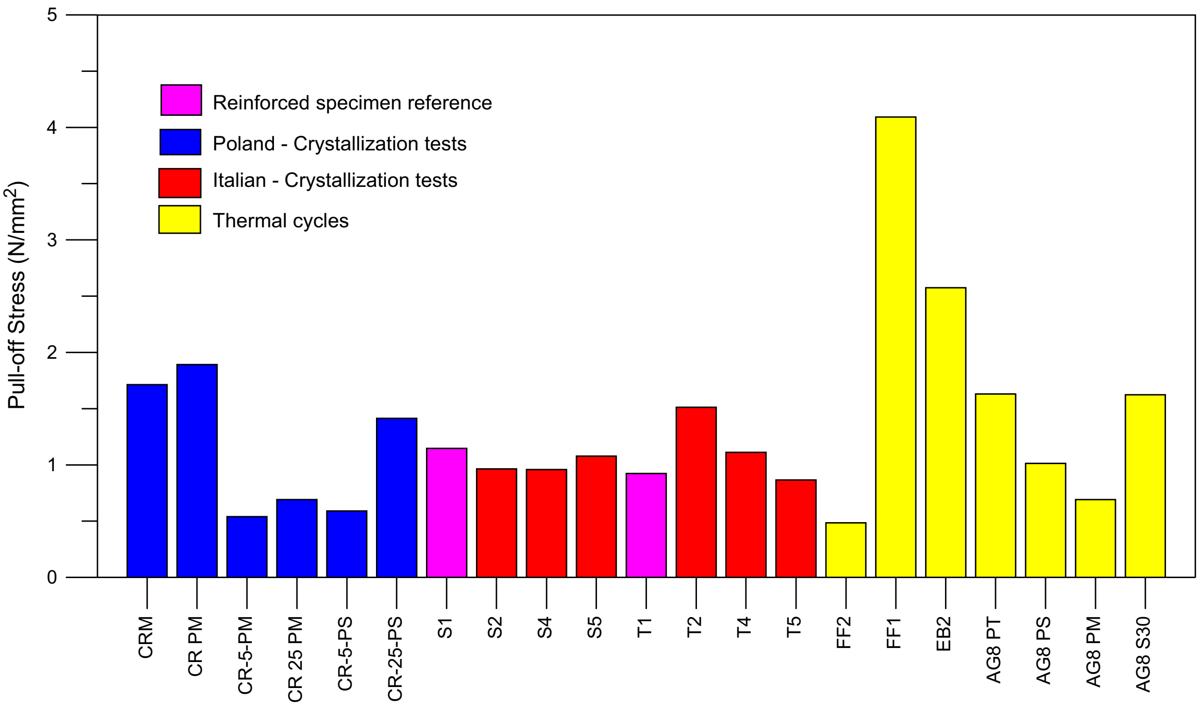

Fig. 11 Mean result of pull-off test after crystallization and thermal tests for Italian and Polish specimens

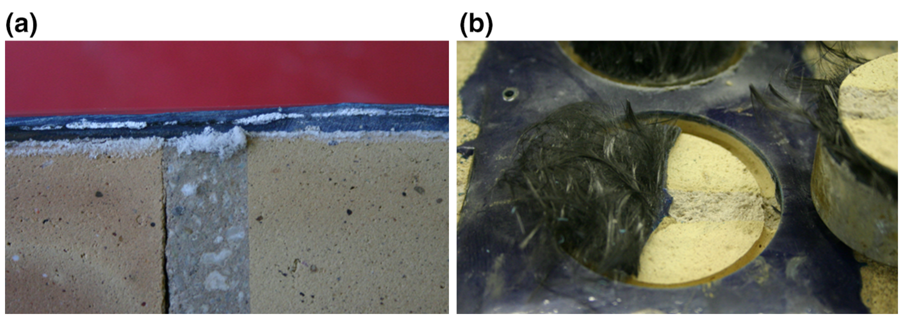

Fig. 12 Damage after 11 cycles of crystallization test for Italian specimens: **a** concentration of salt underneath the fibers, and **b** detached protruding fibre filaments in the pull-off test

In the case of the Italian samples, a failure mode A is observed in general, while in the case of the Polish samples, the failure mode is in general type C–D. Therefore in the first case the failure of the brick is recorded while in the second case the fibres are detached. The latter mode of failure is preferred for cultural heritage applications since through this mechanism, the failure of the substrate does not occur and permanent damage to the structure and material is avoided.

One can observe how the salt crystallisation has occured at the interface between the fibre and the brick, in Fig. 12a, which shows an Italian sample. This phenomenon has not occured in the case where the fibres had a good bond.

8 Conclusion

Durability and bonding of FRP system on masonry is crucial, especially for possible application in historical context, where moisture and consequent salt migration in the substrate can influence the application phases, and where thermal cycles occurring in the environment can cause de-bonding.

Masonry specimens repaired with CFRP strips were subjected to thermal cycles and to sodium sulphate crystallization tests according to a RILEM Recommendation.

Tests on thermal ageing applied with a procedure set on purpose within the research on various types of bricks and composites, showed that some irreversible damage can occur due to the different behaviour of the resin connecting the FRP to the masonry, in case of weak highly porous bricks, as present in the historical context. In case of less porous bricks the damage does not apparently occur. Nevertheless, the aspect of loading in the temperature range close to the characteristic glass transition temperatures of bonding adhesives (especially epoxy resins) has to be taken into consideration, in future research, in order to check the possibility of choosing appropriate resins and FRPs. This aspect should be investigated not only in the unloaded state but also loaded specimens should be taken into consideration during thermal tests.

On some masonry specimens subjected to crystallization tests, after 11 cycles lasting 4 weeks each the effect of the salts damage was surveyed and measured. The damage caused by the salts seems to be higher on the masonry repaired with this technique than on the blank specimens, due to the higher accumulation of humidity and salts around the strips and within them. The salts crystallize as crypto-florescence underneath the depth of penetration of the primal and within the strip itself causing delamination and detachment of the strip.

Nevertheless, not only decrease in strength after salts crystallization was observed but also strength increase. This phenomenon should be investigated in further research, as well as the compatibility and durability of FRP repair.

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References

1. ACI 440M Guide Draft-1 (2004) Guide for the design and construction of externally bonded FRP system for strengthening unreinforced masonry structures. ACI Committee 440
2. Aiello MA, Sciolti MS, Pecce M (2003) Experimental investigation on bond between FRP sheets and natural masonry blocks. In: 10th International conference SF&R-2003, London, UK
3. ASTM C1583 (2004) Standard test method for tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair and overlay materials by direct tension (pull-off method). American Society for Testing and Materials, West Conshohocken
4. Binda L, Charola AE, Baronio G (1985) Deterioration of porous materials due to salt crystallization under different thermohygrometric conditions. In: 5th International conference on deterioration and conservation of stone, Losanna, 1985, pp 279–288
5. Binda L, Baronio G, Tiraboschi C (1993) Repair of brick-masonries by injection of grouts: experimental research. J Struct Eng Madras India 20(1):29–44
6. Binda L, Tedeschi C, Valluzzi MR, Garbin E, Panizza M (2011) Salt crystallization tests on brick masonry reinforced by CFRP textiles. In: 12th International conference on durability of building materials and components (CDROM + book), 12–15 April 2011. FEUP, Porto, pp 855–864
7. Briccoli Bati S, Rovero L (2001) Experimental validation of a proposed numerical model for the FRP consolidation of masonry arches. In: 3rd International conference on structural analysis of historical construction—SAHC 2001, Guimaraes, Portugal
8. Briccoli Bati L, Rovero L (2008) Towards a methodology for estimating strength and collapse mechanism in masonry arches strengthened with fibre reinforced polymer applied on external surfaces. Mater Struct 41(7):1291–1306
9. Cardani G, Tedeschi C, Binda L, Baronio G (2002) Crystallisation test on treated brick/stone masonry specimens for damage evaluation. In: 9th International conference on durability of building materials, Brisbane, Australia, 17–20 March 2002. CD-ROM, paper 039, 2002
10. CNR DT200 (2004) Guide for the design and construction of an externally bonded FRP system for strengthening existing structures. Italian National Research Council CNR, Rome
11. EN 998-2:2010—EN 998-2:2010 specification for mortar for masonry—Part 2: masonry mortar
12. EN 771-1:2011—specification for masonry units—Part 1: clay masonry units
13. Falborski T, Kwiecień A, Piszczyk Ł, Strankowski M, Jankowski R (2012) The influence of temperature on properties of the polymer flexible joint used for strengthening historical masonries. In: Jasieńko J (ed) Structural analysis of historical constructions, 2012. DWE, Wrocław, pp 816–822. ISBN 978-83-7125-216-7
14. ISO 527-1:2012—plastics—determination of tensile properties—Part 1: general principles

15. Klamer E, Hordijk D, Kleinman C (2006) Debonding of CFRP laminates externally bonded to concrete specimens at low and high temperatures. In: Third international conference on FRP composites in civil engineering (CICE 2006), Miami, Florida, USA, 13–15 December 2006
16. Kwiecień A (2012) Stiff and flexible adhesives bonding CFRP to masonry substrates—investigated in pull-off test and Single-Lap test. Arch Civ Mech Eng Elsevier 12(2):228–239 ISBN 1644-9665
17. Kwiecień A (2013) Highly deformable polymers for repair and strengthening of cracked masonry structures. GSTF Int J Eng Technol (JET) 2(1):182–196 ISSN 2251-3701
18. Panizza M, Garbin E, Valluzzi MR, Modena C (2009) Experimental study of the FRP–clay interface subject to normal stresses. In: Proceedings of MuriCo3, 22–24 April 2009, Venice, Italy
19. Panizza M, Garbin E, Valluzzi MR, Modena C (2010) Experimental investigation on local aspects of the FRP strengthening of masonry arches. In: 8th International symposium on the conservation of monuments in the Mediterranean Basin, 8th MONUBASIN, Patras, Greece, 31 May–2 June 2010 (on CD-ROM)
20. RILEM MS-A1 (1998) Determination of the resistance of wallettes against sulphates and chlorides
21. Ulaga T, Meier U (2001) Long-term behaviour of CFRP-laminate-strengthened concrete beams at elevated temperatures. In: Proceedings of FRPRCS-5 conference, Cambridge, pp 147–156
22. UNI 8942-3 (1986) Prodotti di laterizio per murature. Metodi di prova
23. UNI EN 772-1 (2007) Methods of test for masonry units. Determination of compressive strength
24. Valluzzi MR, Valdemarca M, Modena C (2001) Behavior of brick masonry vaults strengthened by FRP laminates. ASCE J Compos Constr 5(3):163–169
25. Valluzzi MR, Garbin E, Panizza M, Binda L, Tedeschi C (2011) Moisture and temperature influence on FRP masonry bonding. In: 12th International conference on durability of building materials and components (CDROM + book), Porto (P), 12–15 April 2011, pp 865–874
26. Valluzzi MR, Oliveira DV, Caratelli A, Castori G, Corradi M, de Felice G, Garbin E, Garcia D, Garmendia L, Grande E, Ianniruberto U, Kwiecień A, Leone M, Lignola GP, Lourenço PB, Malena M, Micelli F, Panizza M, Papanicolaou CG, Prota A, Sacco E, Triantafillou TC, Viskovic A, Zając B, Zuccarino G (2012) Round robin test for composite-to-brick shear bond characterization. RILEM Mater Struct 45:1761–1791
27. Zając B, Kwiecień A (2014) Thermal stress generated in masonries by stiff and flexible bonding materials. In: Proceedings of the 9th international masonry conference in Guimarães, ID_1629