XII DBMC
International Conference on Durability of Building Materials and Components
PORTO - PORTUGAL, April 12th-15th, 2011

Salt Crystallization Tests on Brick Masonry Reinforced by CFRP Textiles

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ABSTRACT

Repair of historic masonry by Fiber Reinforced Polymers (FRP) systems is being more and more used especially in seismic areas. A rather great deal of experimental research on the mechanical behaviour of the repaired masonry has been carried out but very small experimental work has been done on the durability of FRP repairs when masonry is exposed to aggressive environments.

Carbon FRP (CFRP) have been applied on the surface of both soldier course and running bond specimens respectively as bonds in thin vaults and in solid walls. A total number of 20 specimens have been prepared and tested. A RILEM pre-standard procedure was followed for the evaluation of resistance to sulphates of the specimens. The damage evolution has been monitored by visual observation and by quantification of material loss in the vertical section at each 4 week cycle and the first results are here reported which show the importance of a carefulr application of FRPs.

KEYWORDS:

Brick masonry, FRP repair, durability to salt solutions

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1 INTRODUCTION

FRP systems application to historic masonry repair is being more and more used in Italy, especially in seismic areas. FRPs are now preferred to other systems as r.c. and steel due to their light weight and adaptability to complicated shapes [Ajello, 2003]. Even if a rather great deal of experimental research on the mechanical behaviour of the repaired masonry has been carried out [Briccoli Bati, 2001], and a standard exists in Italy for their application [CNR DT 200, 2004] still some doubt remain on the impact of this technique on the authenticity of the historic buildings. Furthermore very small experimental work has been done on the durability of these repairs when exposed to aggressive environments (thermal cycles, high humidity, etc.).

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 [Binda, 1985].

In order to check the durability of FRP systems applied to masonry structures to these phenomena, salt crystallization tests on brick masonry assemblages have been performed [Cardani, 2001].

Carbon FRP have been applied on the surface of both soldier course and running bond specimens respectively as bonds in thin vaults and in solid walls. Considering two tests for each condition plus a reference non strengthened specimen, four different strengthening patterns for each of the two textures have been chosen. A total number of 20 specimens have been prepared and tested.

A RILEM 127MS [RILEM MS-A1, 1998] pre-standard procedure is followed for the evaluation of resistance to sulphates of tested materials. The wallettes were submitted to the salt crystallisation test by immerging them in a sodium sulphate solution and exposing one surface to 20°C and 50% relative humidity (R.H.) in a climatic chamber, then adding water every 4 weeks, in order to create a sort of cycle.

Damage evolution has been monitored by visual observation and by quantification at each 4 week cycle, of material loss by a profilometer. The results show the rising of salt from the uncovered surface since the first week of observation, and also perhaps a concentration of stresses underneath the fibres. Thermographic images of the bonded strips were taken before the test and after 8 cycles in order to compare the eventual evolution of the bond. The specimens have now reached the 8th cycles and the tests will continue for other four cycles. Eventually pull off tests will be carried out on the surviving specimens at the end of the tests. The results obtained after the first 8 cycles are reported in the following with some critical remarks.

2 EXPERIMENTAL

The experimental program aimed at investigating the durability of masonry repaired by FRP to salt crystallisation was proposed within the RILEM TC 243 MSC. and within a the European Contract NIKER (FP7-ENV-2009.1-N.244123).

FRP strips were applied on masonry elements (small assemblages with mortar joints) and tested in the presence of a sodium sulphate solution. The test is simulating an aggressive environment in which salts can arrive into the masonry by capillary rise.

The experimental campaign included the following tests:

1. Crystallisation tests on masonry assemblages
2. Damage measurement with a laser profilometer
3. Bond investigation by a non destructive technique (thermography) which allows to check the connection between the FRP and the substrate.
4. Pull-off tests will be eventually carried out after the end of the cycles on the surviving specimens.

2.1 Test Description and Aims

The aim of the research was the analysis of damage induced by salt crystallisation to the support and to the bond between CFRPs and the masonry in order to predict the effectiveness of the bond adhesion in time, as well as in “real” environmental conditions. Some hypotheses had to be checked: (i)the presence of the stiff and waterproof strips could induce higher damages into the surrounding masonry, (ii) crypto-efflorescence could be formed underneath the strips and bring to the delamination of the strip itself.

2.1.1 Materials choice and preparation of the specimens

Solid units are 56x122x255 mm soft mud facing bricks were provided by Sant’Anselmo (Padova), having a mass of 1400 kg/m^3 and a water absorption of 26% [UNI EN 771-1]. Laboratory tests performed at the University of Padua allowed estimating a mean strength of 16.51 MPa in compression, 4.75 MPa in flexure, 3.39 MPa in splitting tension and 1.27 MPa after direct pull-off. The mortar is a premixed product based on natural hydraulic lime provided by Tassullo (Trento), having (after 28 days) a declared compression and a flexural strength of 3.7 and 1.3 MPa respectively, and Elastic Modulus of 6130 MPa.

Mercury porosimetry tests have been carried out on brick and joint samples. The results are the following: a) total porosity 48 - 28% respectively for brick and mortar, b) median pore radium 0.6822 - 0.3476 μm respectively for bricks and mortar.

Finally, textile MBrace Carbon C5-3 has been applied with Wet Lay Up system, as provided by BASF Italia (Treviso). Carbon fibers are unidirectional and have high modulus (390000 MPa), a tensile strength of 3000 MPa, an ultimate strain of 0.8% and a coefficient of thermal dilation of 10^{-7} K^{-1}. Bicomponent epoxy resins used at the interface compose both the primer and the saturant. Porperties declared by the provider are as follows (obtained after 7 days of curing, at T=20°C and RH=90%). The primer has a compression and tensile strength >40 and >20 MPa, respectively, whereas Elastic Modulus on the same stress conditions are 1900 and 1200 MPa, respectively. The saturant has a corresponding values of >80 and >25 MPa for compression and tensile strength, and 3100 and 3300 MPa for the Elastic Modulus.

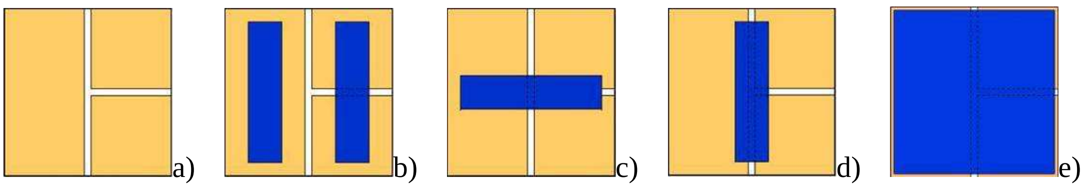

Figure 1. Soldier course specimens for crystallisation tests:a) S1; S1a, plain sample (only brickwork); b) S2,S2a, configuration 1, c) S3,S3a; configuration 2, d) S4, S4a; configuration 3, 4) S5, S5a, configuration 4, FRP covering the whole surface of the specimen.

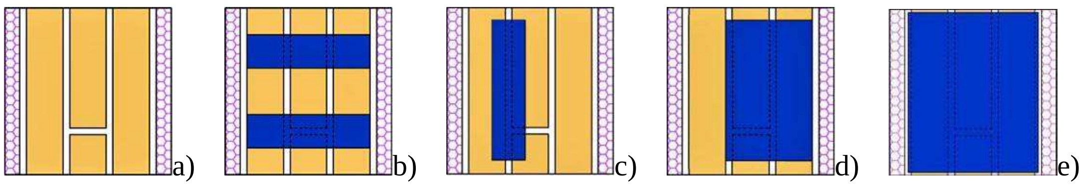

Figure 2. Running bond specimens for crystallisation tests:a) T1; T1a, plain sample, (only brickwork); b) T2,T2a, configuration 1, c) T3,T3a; configuration 2, d) T4, T4a; configuration 3, 4) T5, T5a, configuration 4, FRP covering the whole surface of the specimen.

Two series of specimens have been subjected to the crystallisation tests. Pilot unstrengthened specimens have been considered too, as reference condition. The specimens simulated different bond configuration, as showed in Figure 1 and 2. The specimens were small assemblages simulating diffused masonry textures as:

a) soldier course specimens, with courses of bricks laid with the long sides upright (as in thin vaults),
b) running bond specimens simulating common textures of masonry walls .
For each type of specimens the strips were applied according to four configurations (Fig. 1 and 2). The specimens were called S in the case of soldier course, and T in the case of running bond. For each configuration two specimens a,b were tested.

2.2 Test Procedure

The test was carried out according to the Recommendation RILEM MS A.1 [RILEM MS A1, 1998]. The wallettes (approx. 250x200x120 mm), were put in contact with their bottom side with a 10% (w%) Na_2SO_4 solution (anhydrous Na_2SO_4 reagent grade, Fluka)(Fig. 3a) and then stored over a layer of dry gravel in a plastic container (Fig 3b) open at the top, sealed along the borders (Fig.3c) with the upper face exposed to the environment (controlled laboratory environment of 20°C and 50% R.H.).

After four weeks the first crystallization "cycle" or step was concluded.The wallettes 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, f) reading of the surface profiles by means of a laser profilometer which allowed to quantify the damage, d) thermographic tests before crystallisation and after 7 cycles. De-mineralised water was then added and a new 4-weeks cycles began.

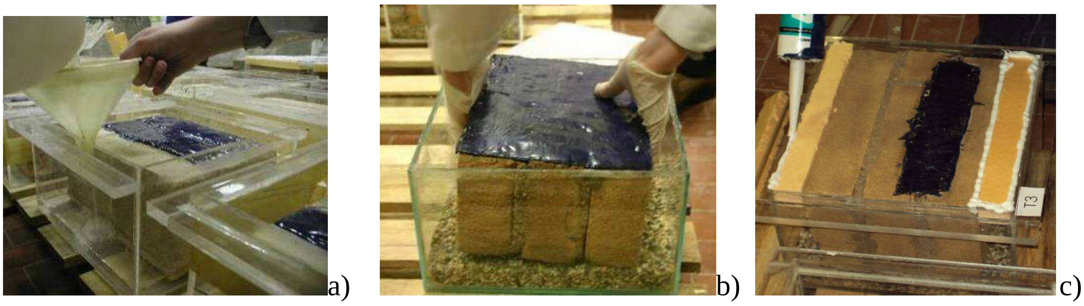

Figure 3. Details of the test: a) salt solution addition b) positioning of the specimen on sand, c)sealing of the box,

2.3 Damage Measurement by Laser Profilometer

A laser profilometer was used to monitor the damage (Fig. 4a) [Cardani, 2002]. The use of the laser profilometer allows to measure, with a very good resolution, the loss of material from the exposed surface, calculated at subsequent times.

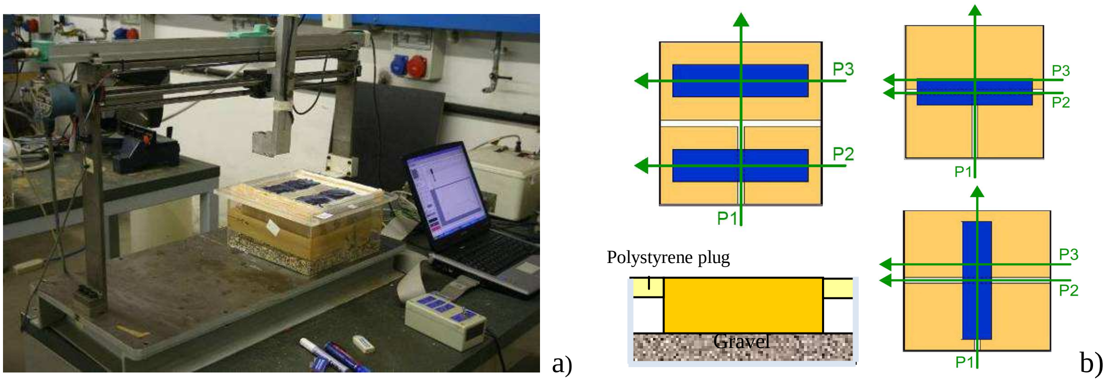

Figure 4. Damage measuring device: a) lasers profilometer, b) scheme of the measurement.

Profiles recorded at the end of each 4-weeks cycle show how the surface is changing during time due to the progress of the decay and the loss of material can be measured by calculating the area loss% between profiles after each cycle [Cardani, 2002].

3 RESULTS AND DISCUSSION

As said above the damage was checked at every four weeks the wallettes were subjected to i) visual inspection and photographic survey, ii) reading of the surface profiles by means of a laser profilometer which allowed to quantify the damage.Subsequrntly the area loss % at each cycle were calculated and the results were copmpared with the blank specimens ones. Furthermore IR thermographic tests were carried out before crystallisation and after 7 cycles in order to detect in a non destructive way possible detachment of the FRP strips after the crystallisation tests.These results were checked by cutting specimen S5. Due to lack of space only the results obtained for the soldier course specimens will be presented and discussed in this work.

3.1 Visual Inspection and Description of Damage

Visual inspection and photographic survey were carried out on each specimen at every four week cycle and pictures were taken before and after brushing the damaged specimen. Due to lack of space here the pictures taken after 7 cycles of the blank specimen and of specimen in configuration 1, S2a are presented in Figure 5 a),b),c),d).

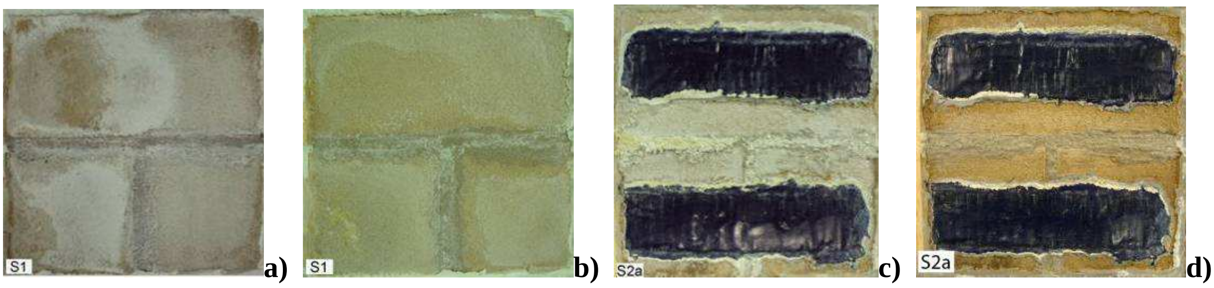

Figure 5. a), b) blank specimen S1 before and after brushing; c), d) specimen S2a before and after brushing.

Some general comments can be made at the end of the 7th cycle. The blank specimens and the repaired ones behaved in different ways even if the types of damage were similar. In Fig.5a),b) the specimen $S_1$is presented before and after brushing. The specimen was covered with salt encrustations on top of the bricks and of the mortar joints. After brushing some delamination of the brick surface was visible. In Fig.5c) and d), the specimen S_2a before and after brushing is presented. Also this specimen was covered of salt encrustations. Outside the FRP strips, the materials were highly humid and apparently a deeper damage was intersting the bricks. Even after brushing salt accumulation around the strips was evident, with some signs of detachment of the trips at the borders.

3.2 Profile Measurements

The profiles measured by the profilometer at cycles 2,3,5,6 and 7 are reported in Figure 6, for the specimens S1 and S2a for profiles P1 In the diagrams, apparent increase in vertical coordinate correspond to bulging of the surface at the starting of delamination and spalling.

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 [Cardani, 2001]. 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. Furthermore; in these cases it seems that a different damage is induced by the presence of FRP which are partially covering the specimen upper surface.

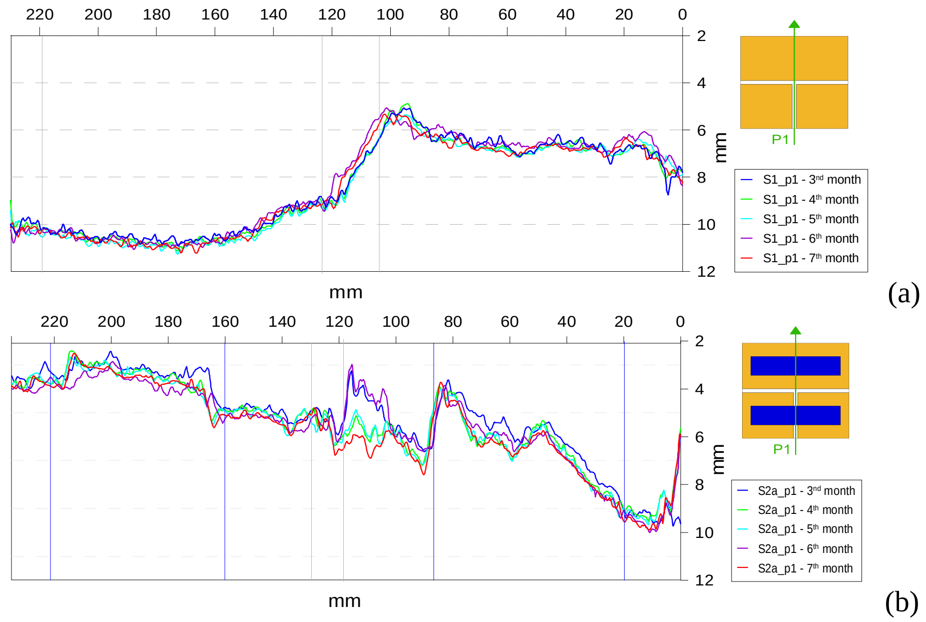

Figure 6. Diagrams of the profiles for specimens S1 (a), and S2a (b) measured at cycles 3, 4, 5, 6 and 7

3.3 Damage Progression under the Crystallisation Cycles

Each profile represents the border of the vertical section of the specimen. The difference between two subsequent profiles at each cycle can be considered as material loss (or apparent increment in the case of bulging) and the calculated area as % of the specimen vertical section can be assumed as damage parameter (loss (%)) and even be used for the implementation of deterministic or probabilistic mathematical models to predict the material behaviour under salt crystallisation damage [Binda et al. 1985].
In Figure 7a the damage diagrams (area lost at each measurement in mm^2) are given. The values were obtained by elaborating the data read by the profilometer for the brick-mortar profile and for the mortar joint. Cleaning of the temporary bulging due to detaching of layers was also carried out The curves show that the specimen MA was the most damaged.

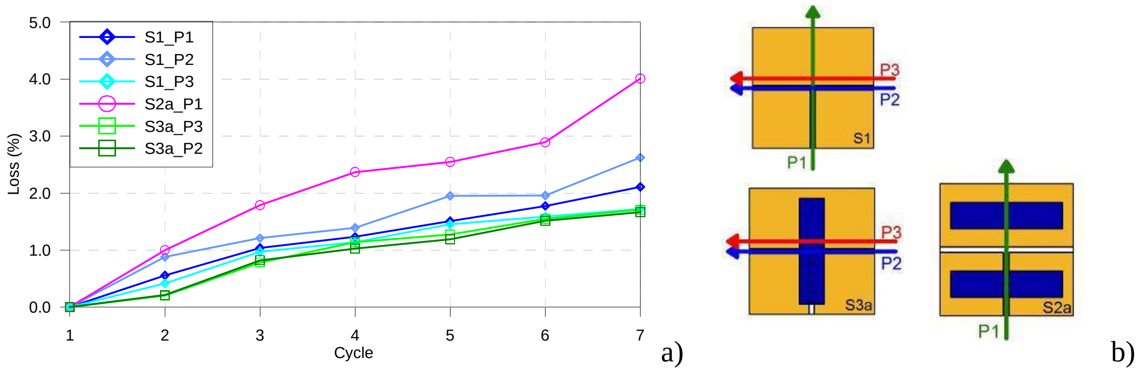

Figure 7. a) Area loss % against number of cycles for some of the obtained profiles, b) specimens and profiles.

3.4 IR Thermography Application

IR Thermography reveals the infrared radiations emitted from a heated surface of an object in a certain time. As a result, a thermal image of the object is obtained, by a color scale or a gray scale. Working in the infrared radiations range, this technique is able to detect the energy emitted by any material in the form of electromagnetic radiations. This property of the materials is strictly connected to their thermal conductivity and their heating capacity: the first parameter determines the capability of a material to transmit heath, while the second one defines the attitude of a material to hold heath.

The thermographic test is based on the acquisition of thermal images by an infrared camera: observing with this device the temporal changes of the surface temperature distribution, near surface characteristics of the material can be detected. To obtain measurable temperature differences on the surface of the observed element, a previous heating of the material is necessary. It can be done by solar radiation (passive method) or using heating systems (active method). Recording images during the cooling down phase, when the solar radiation is no more present or after removing the heating source, the results are detectable. Differences in the distribution of the temperature on an area that has been previously heated in uniform way can be connected with significant information concerning the composition and the presence of defects in the structures of traditional buildings.

All the specimens were submitted to IR thermography before and after testing and the images were restituted by an infrared camera Nec-AVIO TVS 500E model equipped with a photographic camera, based on a detector formed by a matrix 320 (H) x 240 (V), Vanadium Oxide microbolometer type. The spectral field of this device is 8 – 14 μm.

The first thermography was carried out on specimens dried into the oven at constant mass and gives a rather uniform deistribution of temperatures. It is possible to to see that some bond original defects were present before the tests on S3a and S5a in coincidence with the joints.The second one was madeafter 7 cycles; the specimens were heated with a IR lamp. Of course they were wet due to the presence of sodim sulphate. So a direct comparison was not possible. Nevertheless Figure 8 shows the presence of humidity at the external perimeter of the FRP strips and it can be hypothised that detachments are taking place around (Fig.8a,b,c) and even under the FRP (Fig.8 d)

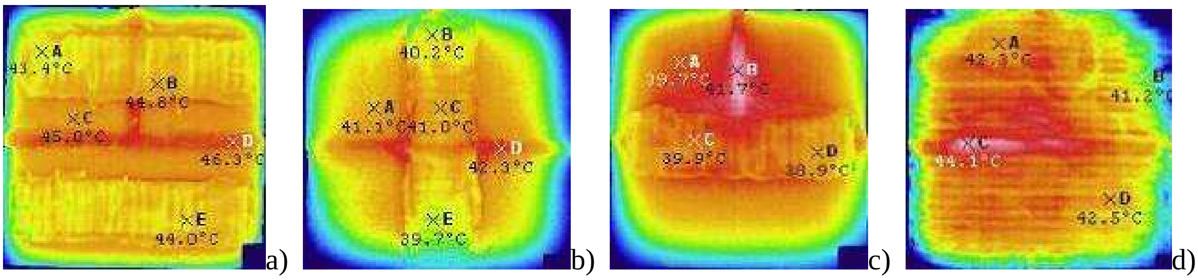

Figure 8. Thermographic restitution of S2a, S3a, S4a, S5a upper face, dried in oven before the cycles

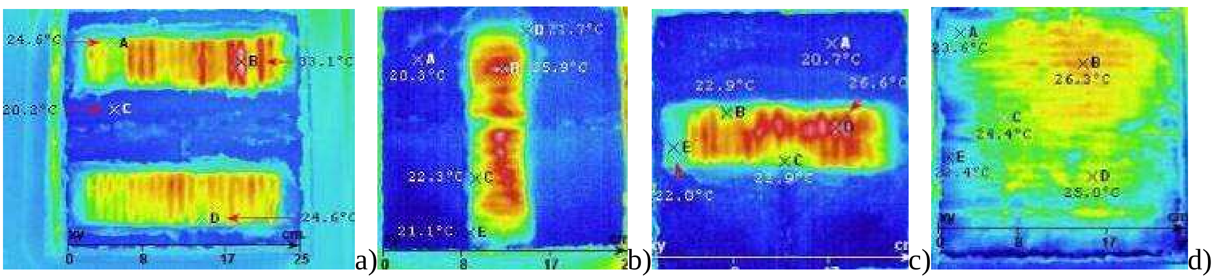

Figure 9. Thermographic restitution of S2a, S3a, S4a, S5a upper face after 7 cycles

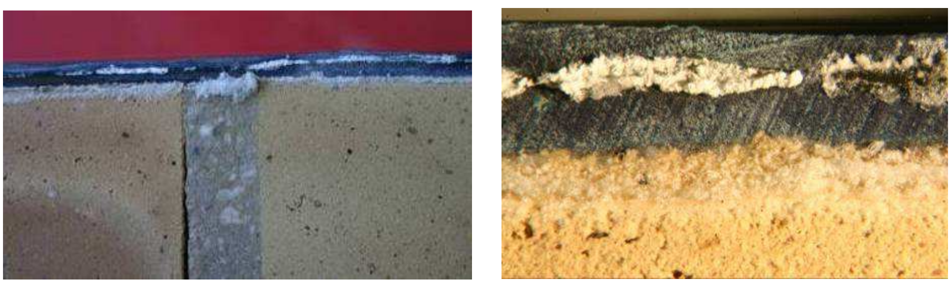

Figure 10. A vertical section of the specimen upper surfaces. Subefflorecence at the depth of penetration of the primal into the brick and within the FRP strip

Specimen S5a was cut in order to check the results of thermography (Fig.9) It is possible to see that the salts crystaòllise underneath the external surface causing a double damage: a) at the penetration depth of the primal and b) within the FRP itself with its delamination and detachment from the masonry specimen.

4 CONCLUSIONS

Masonry specimens repaired with CFRP strips were subjected to sodium sulphate crystallisation tests according to a RILEM Recommendation. After seven steps (cycles) of the test lasting each four weeks the effect of the salts damage were surveyed and measured by the use of a laser profilometer. The damages caused by the salts on the bond between FRPs and the masonry and under the FRPs were also detected by using IR thermography as NDT. Some comments can be drawn even if the tests will still continue:

- The damage caused by the salts seem to be higher on the masonry when repaired with this technique than on the blank specimens, due to higher accumulation of humidity and salts around the strips and withing them.
- The salts crystallise as cryptoflorescence underneath the depth of penetration of the primal and within the strip itself causing delamination and detachment of the strip.
- Further tests are needed in order to check whether the type of application of the strip can influence the results.

ACKNOWLEDGMENTS

The experimental work is included in the activities of the Rilem 223MSC TC “Masonry Strenghtening with Composite Materials” www.rilem.net and is also supported by the EC Contract NIKER (FP7). Authors wish to thank Basf (Treviso) for supporting composite materials, S.Anselmo Laterizi (Padova) and Tassullo (Trento) for providing bricks and mortar, respectively; M. Beggiato, A. B. Silva, S. Perego, M. Taccia, M. Cucchi e M. Iscandri, are kindly aknowledged for their contribution in the laboratory phases and analyses.

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