IMEKO International Conference on
Metrology for Archaeology and Cultural Heritage
Lecce, Italy, October 23-25, 2017

Bond analysis of thermally conditioned FRCM-masonry joints

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***Abstract* – Results of an experimental investigation on bond between thermally conditioned FRCM-masonry joints is presented and discussed in the paper. Single lap shear tests were conducted on clay brick specimens strengthened with different FRCM systems (basalt, steel and PBO-FRCM systems). Before testing specimens were thermally conditioned by exposure to different temperature values: 20°C (ambient temperature), 100 °C, 150 °C and 200°C. The thermal treatment was developed in this way: strengthened specimens were kept in oven and exposed to constant temperature over a period of three hours, then, they were removed and cooled down freely to ambient temperature. After the thermal treatment, specimens were tested at ambient temperature.**

Experimental results allow to evaluate the influence of the thermal conditioning on the local bond-slip response of strengthened specimens.

I. INTRODUCTION

The interest in fiber reinforced cementitious matrix (FRCM) in construction has considerably increased, especially the application of FRCM as externally bonded reinforcement for concrete and masonry structural strengthening and rehabilitation. The static behavior of reinforcement in FRCM has been extensively studied in the literature, while the influence of service conditions, as the exposure of high temperatures on the structural performance, represents an open topic that needs to be analyzed in more detail.

The effect of fire and high temperature on the mechanical behavior and properties of reinforced concrete has drawn considerable attention in recent research studies [l-3]. The studied properties include compressive strength [4], modulus of elasticity [5], shear modulus [5], thermal conductivity [6], specific heat [6] and creep [7] of concrete along with modulus of elasticity [8] and coefficient of thermal expansion and tensile strength [9] of reinforcing steel.

However, there are few studies on masonry, in particular information on the influence of the high temperature on bond between masonry and fabric is limited.

The correct understanding of the bonding behavior of textiles with cement-based matrices is an important step in comprehending the degrading mechanisms that a composite can suffer when subjected to elevated temperatures.

Recent studies [10, 11] was focused on the influence on the bond of the thermal damage due to exposure of PBO-FRCM/TRM strengthened system to elevated temperature. The exposition ad high temperature has shown a sensible reduction both of the failure load and the rigidity of the strengthening system.

In this paper, first results of an appropriate experimental study based on single-sheet shear bond test on brickwork with different fibers were presented and discussed. Bond tests were conducted on masonry clay bricks specimens strengthened with basalt (with two different mass densities), steel and PBO FRCM systems, thermally conditioned by exposure to different temperature values (*20°C, 100°C, 150°C* and *200°C*).

Results of tests allow to investigate the influence of the temperature on the bond behavior of masonry-FRCM joints.

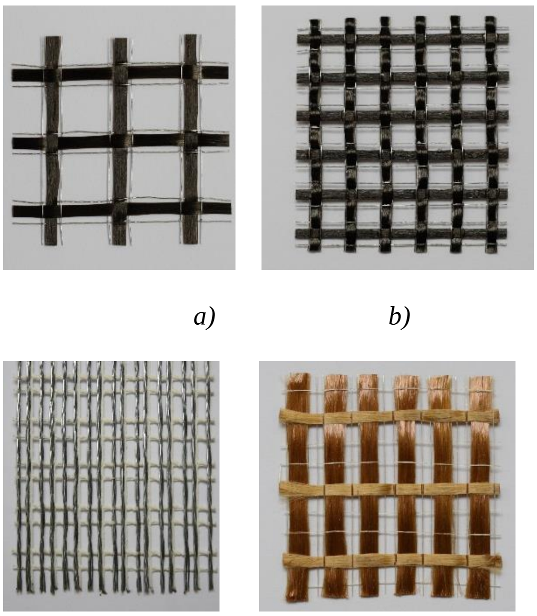
II. MATERIAL PROPERTIES AND TESTING SETUP

The FRCM composite system is composed of fabric meshes embedded in a cementitious mortar. Different FRCM strengthening systems have been used in this investigation: mechanical properties of each system are reported in Table 1 in terms of density, elastic modulus, E_f, tensile strength, f_{fu} and strain,ε_{fu}. In Fig. 1 are depicted the fiber meshes used in this experimental campaign.

Direct shear tests were performed on brickwork substrate applying externally the composite strip. Sixteen specimens were tested by the classical push pull configurations where the brickwork was restrained while the fibers were pulled.

Table 1. Mechanical properties of FRCM systems

FRCM system	Density (g/m^2)	E_f (GPa)	f_{fu} (MPa)	ε_{fu} (%)
B2	200	>70	>1700	>1.9
B4	400	>70	> 1700	> 1.9
S12	1200	190	>3000	> 2.0
PBO		270	5800	2.15



a) *b)*

c) *d)*

Fig. 1. Fabric mesh: a) B2, b) B4, c) S 12, d) PBO

The strengthened system was applied on the all the faces of the masonry prismatic specimens using as bonded length l_b = *300 mm*. The fibers mesh was embedded between to *5 mm* tick layers of matrix as suggested from manufacturers [12-13]

The matrix was bonded starting at a distance of *30 mm* from the brickwork edge at the loaded end (Fig. 2), moreover, two aluminum plates with width of *50 mm* as the width the specimens tested and length of *60 mm* were attached to the end of the bare fibers at the top of the masonry prism using an epoxy resin to improve gripping of the fibers to the testing machine (see Fig. 2). Moreover, the aluminum thick tabs were smoothed of 3 mm to ensure a uniform load distribution.

Two Linear Variable Differential Transducers (LVDTs, named a and b) mounted on the masonry prism adjacent to the bonded length of the composite were used to measure the slip of the fibers with respect to the masonry support. The LVDTs measure the reactions of aluminum L-shaped plate glued to the bare fibers just outside the bonded area (Fig. 2). This average of the values measured by LVDT a and b are called global slip *s*, defined as the relative displacement between the fabric of the composite just outside the bonded area and the close the masonry unit.

The specimens are named following the notations DS_N_T, where the DS indicates that specimen was tested in single-lap direct-shear, N indicated the type of the fibers used, and T indicate the exposition temperature.

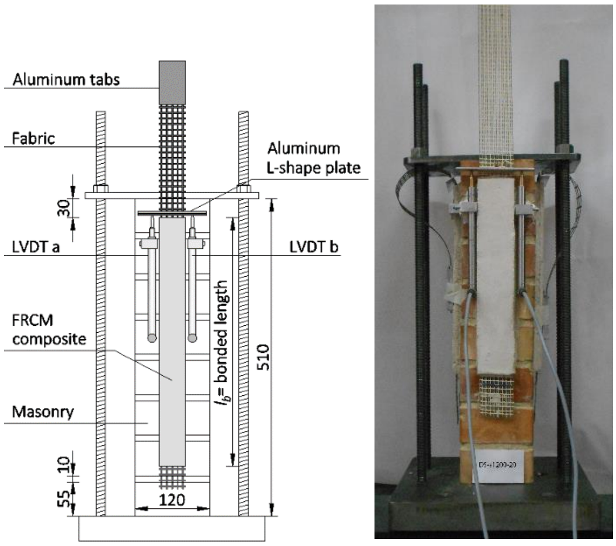


Fig. 2. Test Set-up.

The strengthened specimens were left to cure at room condition (Temperature, *T=20°C*, Relative Humidity, *RH = 65%*) at least *7* days before testing to prevent any unwanted relative thermal expansion which could result to the premature cracking of the prisms.

The tests of single-lap/single-prism specimens were conducted at ambient temperature (*20°C*) for all specimens, and after their exposure at different (nominal) air temperature levels, namely at *100°C*, *150°C* and *200°C*. For each level, a lengthy temperature rise rate (*2°C/min*) was opted for the achievement of the target temperature at which the specimens remained for three hours.

The specimens exposed at high temperature were protected at top and bottom) cover cap by aluminum-lined mineral wool consisted of *50 mm*-thick pieces of and fixed into place by use of specific high temperature tape (Fig. 3). All specimens were tested under axial tensile load in stroke control at a rate of *0.003 mm/s* [12].

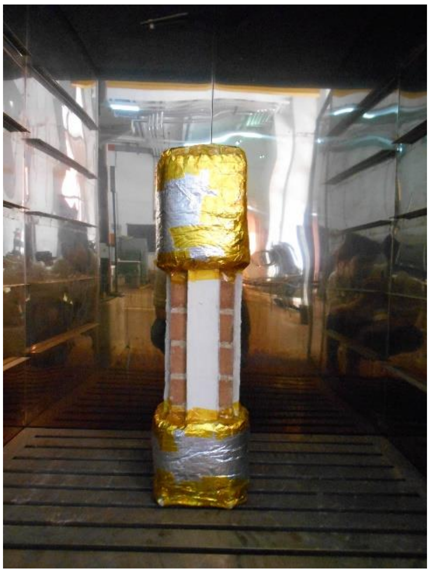


Fig. 3. Specimen covered in electrical furnace.

III. EXPERIMENTAL RESULT AND DISCUSSION

Details of the tested specimens as the temperature value, the peak load P, and the peak stress σ (by the Equations 1) at peak load were summarized in Table 2.

In addition, the peak stress σ^* was defined from the following Equation (1):

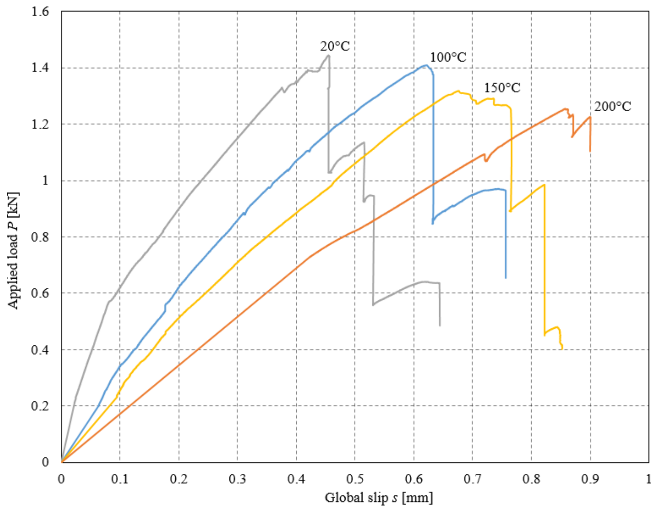
$$\sigma = P / nbt^* \tag{1}$$

where b t^* is the cross sectional area of a longitudinal fiber bundle, and n is the number of bundles in the longitudinal direction.

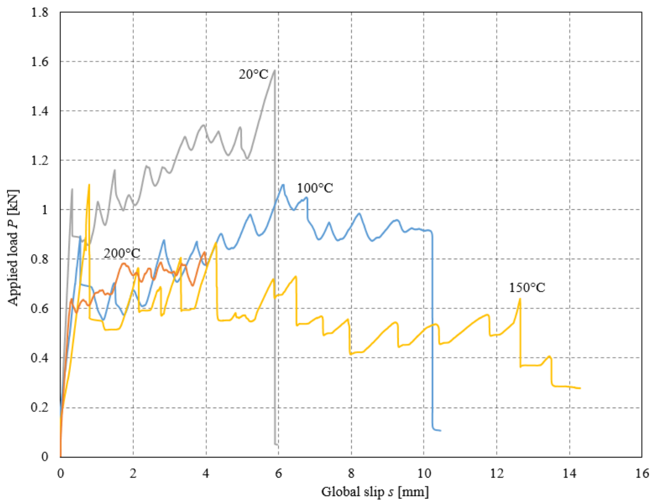
Table 2. Direct shear test results.

Specimen	Temperature	P [kN]	σ [MPa]
DS_B2_20	20°C	1.44	882
DS_B2_100	100°C	1.41	864
DS_B2_150	150°C	1.32	809
DS_B2_200	200°C	1.25	766
DS_B4_20	20°C	1.57	475
DS_B4_100	100°C	1.10	333
DS_B4_150	150°C	0.89	270
DS_B4_200	200°C	0.83	251
DS_S12_20	20°C	6.98	763
DS_S12_100	100°C	6.51	712
DS_S12_150	150°C	4.83	528
DS_S12_200	200°C	4.83	528
DS_PBO_20	20°C	6.40	2320
DS_PBO_100	100°C	5.57	2020
DS_PBO_150	150°C	4.88	1770
DS_PBO_200	200°C	4.19	1520

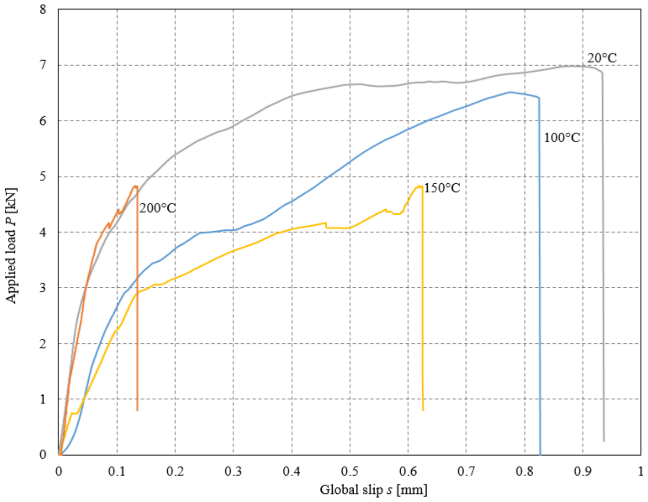
In Fig. 4 were reported the typical response applied load, P versus global slip, s, for each strengthening system adopted in this study.



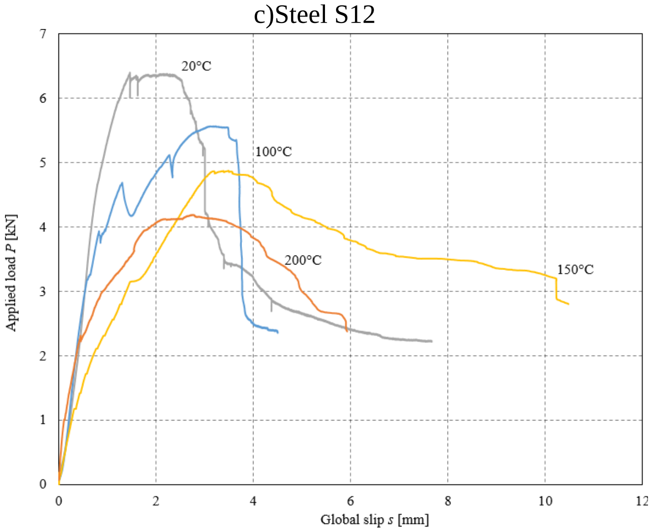
a) Basalt B2



b) Basalt B4



c)Steel S12



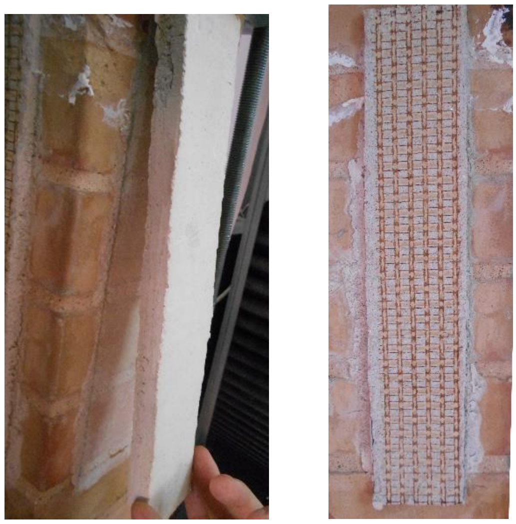
d)PBO

Fig. 4. Applied load P versus global slip s response: a) B2, b) B4, c) S 12, and d) PBO.

It can be noted in Fig. 4 that specimens exposed at different temperature present a considerable reduction in terms of the peak load *P* and an increase of the global slip *s* (for the B2, B4 and PBO) if compared with specimens at ambient temperature. The reason is due to the drop of bond between the two layers of matrix and the fibers (Fig. 5a).

Instead for steel fibers, the global slip decreased with the increase of the exposure temperature. This is probably associated to the drop of bond between the masonry substrate and the composite strip (Fig. 5b).

It has been observed the typical failure of debonding both for the basalt B2 and B4 FRCM systems and the steel S12 system. The failure was characterized by a sudden and brittle detachment of the fabric strip and external matrix layer. For all specimens, the interfacial crack formed along the fabric. Debonding occurred at the internal fabric-to-matrix interface and it was the result of fracture of the matrix between the fiber bundles. Longitudinal and transversal cracks generally formed near the composite loaded end. Then, additional cracks formed progressively towards the composite free end with increasing global slip.



a) b)

Fig. 5. Typical failure mode at 200°C: a) basalt B4 fibers, and b) steel S12.

a) b)

Fig. 6.PBO fiber at 200°C: a) after the exposition, and b) failure mode.

For the PBO fiber net, the typical failure modes show the slippage or the tensile failure of the yarns. In some cases, the combination of slippage and tensile failure of the yarns has been observed at same moment. Besides, the failure occurs in the reinforcement at the textile interface or yarn level, and the substrate or the reinforcement–substrate interface is not involved in the failure mode.

In addition, for the PBO fiber, the exposure at the *200 °C* temperature caused a slight deterioration of the outer fabric (that outside the composite strip) and hence an atypical premature rupture for these types of fibers (Fig. 6).

In the Figures 7 and 8 is reported the comparison between applied load-global slip curves obtained for each strengthening systems for two different values of the temperature (*T=20 °C* for curves in Fig. 7 and *T= 200 °C* for curves in Fig. 8).

It can be noted that the S12 FRCM system and the PBO FRCM system have a remarkable response in terms of peak load P with respect to the basalt fibers.

In terms of global slip s, the B4 FRCM system have similar values of PBO FRCM system. This is mainly due to the internal slippage between the fibers in a single yarn (telescopic behavior), while for the B4 FRCM system, it is due to the fiber slip inside the composite strips (as previously described).

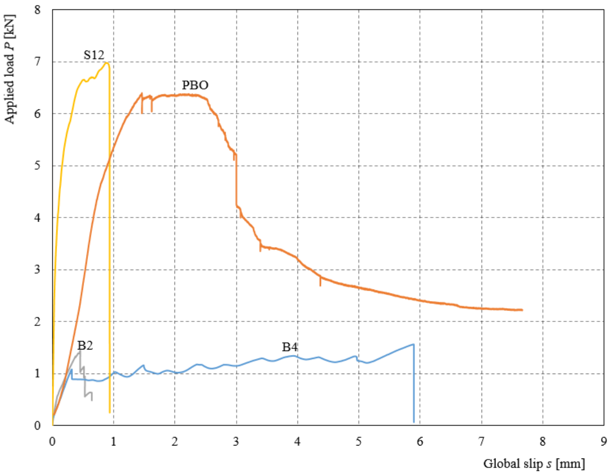


Fig. 7. Applied load P versus global slip s for all FRCM systems tested. (T=20°C)

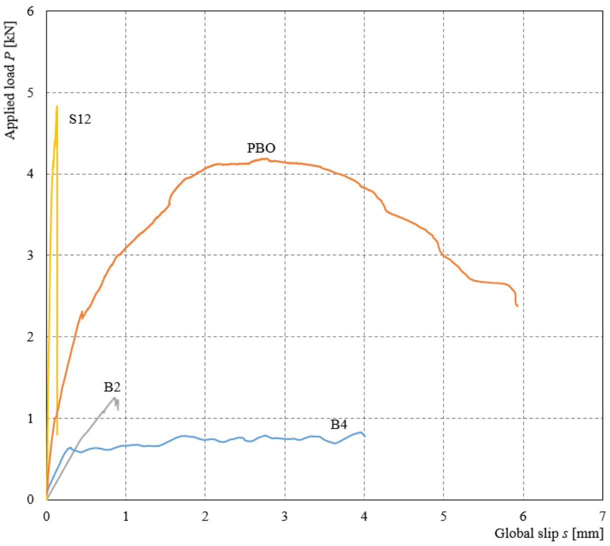


Fig. 7. Applied load P versus global slip s for all FRCM systems tested. (T=200°C)

IV. CONCLUSION

In the present paper, the influence of the thermal conditioning on the local bond-slip response of FRCM to masonry joint has been analyzed by preliminary results of an experimental investigation. Four different types of thermally conditioned FRCM systems have been tested under direct shear bond tests. Increasing the temperature values, a strong decrease in terms of applied load *P* and global slip *s* has been evidenced by test results. This phenomenon is attributed to a loss of adhesion between the fibers and the two layers of matrix and between strips and the masonry substrate. For the B2 FRCM system, it is less highlighted, because of a greater penetration of the fibers in the two matrix layers.

Acknowledgements.

The authors would like to express their appreciation to Ruredil S.p.A. of San Donato Milanese, Italy and Kerakoll S.p.A. of Sassuolo, Italy that provided the composite materials in this study.

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