The role of concrete substrate roughness on externally bonded Fabric-Reinforced Cementitious Matrix (FRCM) layers

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Abstract

Fabric-Reinforced Cementitious Matrix composites represent a promising solution for the strengthening and the upgrading of existing concrete structures. The bond-slip behavior of the FRCM-substrate interface plays an important role in the effectiveness of the reinforcement application. This paper is devoted to understanding the effect of the substrate roughness – obtained in this case by means of a hydroscarification of concrete surfaces with different water pressure stages – on the bond behavior at the interface level, by performing single lap shear tests with a very limited anchorage length. A proper surface machining can increase the roughness of the substrate, ensuring a better interaction at the interface layer, thus preventing premature delamination failures.

Introduction

In Italy, the recent promulgation of novel Italian standards allows designers to use Fabric-Reinforced Cementitious Matrix (FRCM) materials to upgrade and to restore the load-carrying capacity of existing concrete and masonry structures. According to the prescription of a newly introduced Italian guideline [1-2], it is mandatory to qualify FRCM systems with a series of experimental tests, before employing them in structural applications. The wide-spreading in the use of these materials is showing new important aspects that deserve particular attention and investigation; one of them is the bond-slip behavior of such materials since it plays a fundamental role in ensuring the effectiveness of the reinforcement application, preventing weak mechanisms such as delamination failure.

Regarding the application on concrete structures, the most important aspect is the preparation of substrate surfaces. Hydroscarification, which consists of partial removal of the external layer of concrete by using a pressurized water jet, is considered as the best machining option to obtain an adequate roughness of the substrates.

In this paper, a preliminary study on the bond-slip behavior of FRCM materials applied to substrates comprising different surface finishes obtained by means of hydroscarification at increasing pressure levels is presented. The aim is to assess the optimum pressure level that guarantees the full exploitation of the FRCM capacity and to understand whether is possible to geometrically describe the interface surface roughness with a limited number of parameters.

Following the mechanical characterization of the base and the composite materials, a profile roughness analysis is presented. In the end, the bond capacity of the FRCM reinforcement application is assessed by means of a series of shear single lap test.

This study is a part of a broad experimental campaign focusing on the use of FRCM materials in the strengthening and the retrofitting of concrete members (i.e. slabs, slender beams and deep beams), both in monotonic and cyclic loading conditions.

1 Materials characterization

The material used to realize the substrate specimens was an ordinary concrete, characterized by an average cylindrical compressive strength of 46.69 MPa (std. of 4.47 MPa, 9.57%), evaluated by means of eight compression tests on nominally identical cube specimens (100 mm in size). The scatter of the compressive strength results is probably depending on the different casting date since a lower bound of 40.46 MPa was observed in a particular set of specimens. This rather high compressive strength, unusual for existing concrete structures, was chosen to allow to explore even high water pressures in the hydroscarification process, without destroying the concrete substrates.

The FRCM reinforcement system was made of an Alkali-Resistant (AR) glass double leno weave fabric, coated with epoxy resin and embedded in a thixotropic shrinkage-compensated cementitious mortar. The fabric grid spacing was 38 mm, the equivalent reinforcement thickness was equal to 0.093 mm and the average maximum tensile load, obtained by means of four tensile tests performed according to the strip method [3] in displacement control at a stroke rate of 0.01 mm/s on 70 × 400 mm^2 strips, was equal to 12.50 kN. The results of the tensile tests are displayed in Fig. 1(left) in terms of stroke vs. load. The repairing mortar is characterized by an average compressive strength of 58.94 MPa, a flexural tensile strength of 7.02 MPa and an elastic modulus, declared by the manufacturer, of 28 GPa.

Regarding the FRCM system, three warp-reinforced specimens (70 × 400 × 9 mm^3 in nominal size) were tested in uniaxial tension after at least 28 days of natural curing. The tests were performed in displacement control, imposing a stroke rate of 0.02 mm/s. The responses in terms of load-stroke (on 300 mm of free length) are depicted in Fig. 1(right); the average maximum load reached is equal to 9.13 kN, resulting in an efficiency of the composite in the warp direction of 0.73 (evaluated as in [4]).

Other geometrical and mechanical properties of both the base materials and the composite system, together with the setup configurations, are reported in [4].

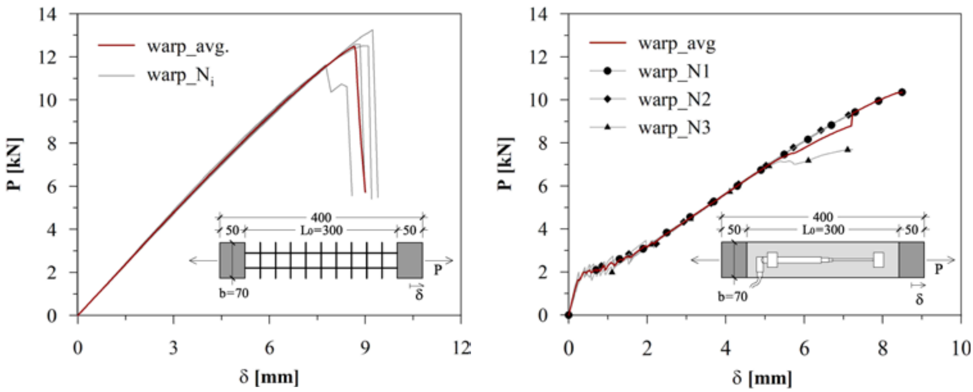

Fig. 1 Average tensile responses of the plain AR-glass fabric (left) and of the FRCM system in terms of load vs. stroke in the warp direction.

2 Substrate machining and roughness analysis

2.1 Substrate machining and profile measuring

The concrete substrates (400 × 200 mm^2 of surface) were subjected to hydroscarification, Fig. 2(left), that consists in removing a portion of the outer concrete layer, in order to introduce adequate roughness at the interface with the repairing composite. Different levels of water pressure, ranging from 200 to 2000 atm as specified in Table 1, were used. This technique, also called hydrodemolition, is the one suggested for large area removals of concrete in preparation for a bonded overlay; compared to other procedures such as grinder, formation of a grid of groves or sandblasting [5], it has the advantage of removing unsound concrete, leaving in place only the high quality material [6]. This process was chosen in place of sandblasting, with a view to reducing the probability of delamination failure of the reinforcement [7], thanks to the greater surface roughness achievable. In order to obtain a homogenous substrate with a surface asperity directly related to the pressure degree, the machining was carried out by the same operator, following an identical procedure; all the substrates were prepared by orienting the water jet towards the surface only one time, following parallel longitudinal lines. In this way, it was possible to prevent a local increase of the bond capacity due to the presence of groves perpendicular to the pull-out direction, investigating only the effect of the set water pressure.

The measuring of the profile roughness of the prepared substrates was done by means of a Laser Optical Displacement Sensor (with a resolution of 5 μm to 25 μm, respectively for static and dynamic measurements), mounted on a two-arms steel framework, Fig. 2(right). Thanks to the presence of two electric motors, it was possible to control the position of the laser sensor in the two perpendicular directions (x and y axes). Modifying the velocity of the sensor motion, it was possible to change the step of the measurement grid. In this case, a 0.5 × 0.5 mm^2 grid was assumed, in order to describe the surface profile with a high level of approximation, also in presence of fine-grained aggregates (in the mix design 0÷15 mm diameter aggregates were used). Attention was given to the planarity of both the bottom steel plate, where the concrete blocks were placed and the two arms of the framework, where the laser sensor was mounted. Moreover, the sensor-substrate distance was checked to fall within the measuring range of the transducer (from 45 mm to 95 mm from the sensor position) before starting the acquisition.

Fig. 2 Example of hydroscarification of a concrete substrate (left). Roughness measurement: laser optical sensor and specimen positioning (center) and two-arms steel framework (right).

2.2 Definition and evaluation of roughness indices

After the measuring of the distance (along the z vertical direction) of each point of the substrate with respect to the laser sensor position, some amplitude parameters were computed in the attempt to synthesize the features of the surface finish in a small number of values. In the end, the graphical representation of each surface helps to interpret the trend of the analysis results.

All the parameters used were computed with respect to the mean plane, R_m, the position of which was defined as the average distance measured by the laser sensor for each surface. This choice was preferred over the interpolating plane, because in this way the R_m plane results parallel to the bottom steel plate of the framework and, especially, to the textile plane after the FRCM application.

The three parameters used in the analyses, in accordance with the 1D definition specified in [8] are:

- R_A, the arithmetical mean absolute deviation of the detected profile from the mean plane;
- R_T, the vertical distance between the highest point of the profile peak, R_P, and the lowest point of the profile valley, R_V;
- R_{5P}, the distance between the two parallel planes passing through the five higher local peaks and the five lower local valleys. In this case, the entire surfaces were divided into 10 × 10 mm^2 zones and, for each one, local peaks/valleys were evaluated.

A graphic representation of these parameters on a random 1D profile is depicted in Fig.3 (left).

The measurements were performed on the entire surface of each substrate specimen but, to exclude the edge areas overly damaged by the hydroscarification, 20 mm wide zones measured from the surface perimeter were neglected. The roughness parameters were also evaluated only considering the contact zone where the FRCM reinforcement was applied, so as to be more representative in studying the relation between the substrate finish and the bond capacity obtained performing shear single lap tests.

In Fig. 3(right) and in Fig. 4, the roughness parameters evaluated for each specimen are plotted at different hydroscarification pressures. It is possible to observe that their values follow the expected trend since to a greater pressure level corresponds an increase of the obtained substrate roughness. This observation seems to be also confirmed by the contour plots of the contact zones in terms of distance from the respective mean plane (Fig.5), where it can be noticed the presence of greater gradients between different points of the surfaces treated with higher water pressure.

Specimens 2B and 3A are exceptions to the observed trend; the levels of roughness detected are higher than the expected ones. The reasons of this are, respectively, a local valley of the profile, probably related to the removal of a large diameter aggregate during the hydroscarification (blue zone in Fig. 5(left)), and a lower compressive strength of the substrate concrete (lower bound of the compressive strength of specimen 3A documented in the materials characterization section). Moreover, it is interesting to observe that the local exceptions are less visible in the R_{5P} index trend, being it narrower than the R_T one.

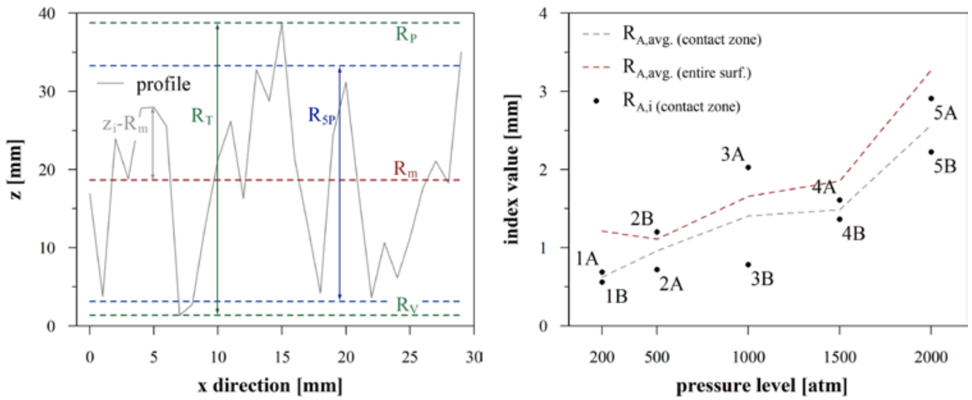

Fig. 3 Roughness indices definition for a random 1D profile (left) and evaluation of the R_A index for the different substrates (right).

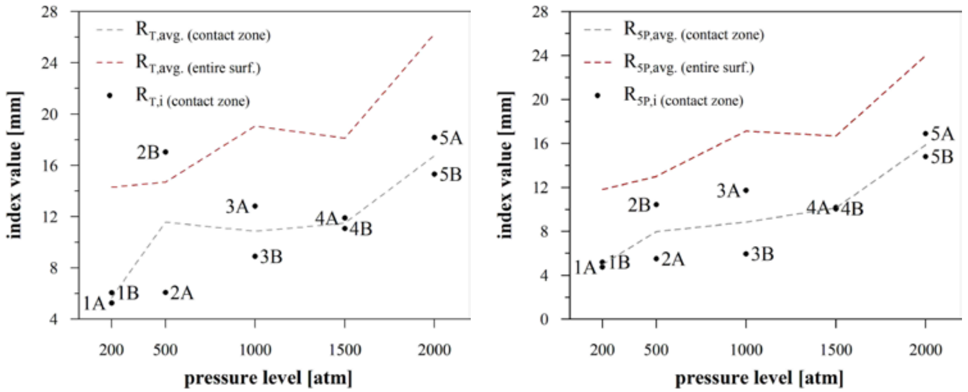

Fig. 4 Evaluation of the R_T (left) and R_{5P} (right) indexes for the different substrates.

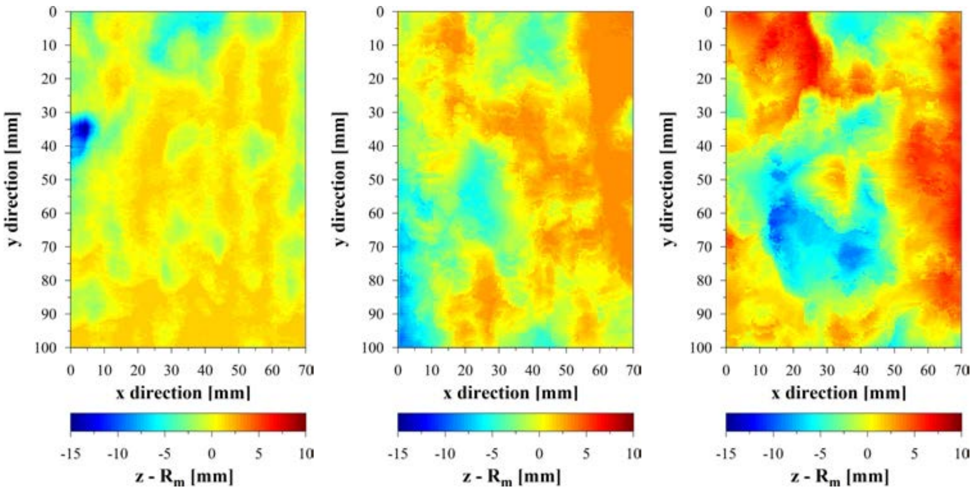

Fig. 5 Contour plot of the hydroscarificated surfaces in the contact zone, in terms of distance of the profile from the corresponding mean plane, for specimens 2B (left), 3A (center) and 5A (right).

3 Single lap shear tests

The FRCM reinforcement layers were cast by means of a typical hand lay-up technique, carried out on the different hydroscarificated concrete blocks after adequate preparation of the contact surface comprising dust removal and saturation. Such processing is necessary to obtain a correct adhesion at the interface level and to prevent the concrete base from rapidly absorbing the water contained in the fresh-state repair mortar. Please note that all the fabrics were placed with the warp direction parallel to the applied load and the textiles were accurately prepared to be clamped, creating an epoxy resin tab at the top end.

After at least 28 days of curing, shear single lap (SL) tests were carried out under displacement control, at 0.01 mm/s stroke rate. The test setup, Fig. 6(left), was the same used in [9] and two Linear Variable Differential Transformer (LVDT) transducers were placed among the concrete substrate and the head of the FRCM layer, so as to measure the global slippage of the reinforcement.

The contact area was nominally equal to 70 × 100 mm^2, while the nominal thickness was equal to 10 mm. Due to the small dimension of the applied reinforcement and the thixotropy of the repair mortar, it was difficult to control the thickness of the specimens; in fact, the average measured size resulted equal to 14.44 mm (std. 1.09 mm). The position of each textile was controlled during the casting by interposing acrylic plates, in order to guarantee in all the tests a rather constant eccentricity of the glass fabric with respect of the reference surface.

The choice to use a limited anchorage length, equal to 100 mm, was done to promote the detachment of the reinforcement as a result of the shear tests; this allowed to better highlight the effect of the substrate roughness on the bond-slip behavior. The increase of the anchorage length, in fact, has a significant effect on the bond capacity [10]; the literature documents that the bond strength increases as the effective anchorage length increases, up to values of 200-300 mm beyond which the benefit becomes marginal [5]. In Italy, in the absence of specific indications of the mortar manufacturer, FRCM reinforcements must be characterized by a minimum anchorage length of 300 mm, as prescribed by [2].

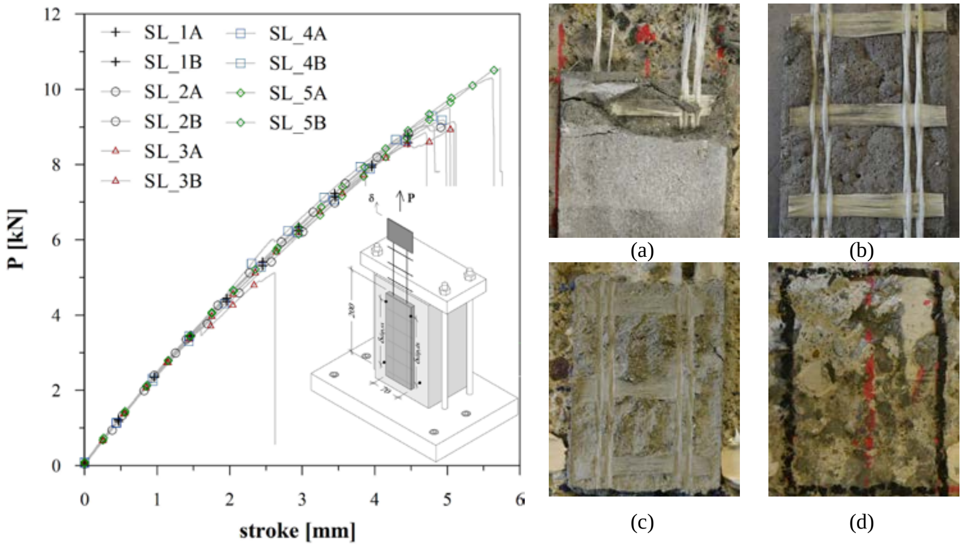

Fig. 6 Comparison between the responses of the single lap shear tests in terms of load vs. stroke for each specimen (left) and example of different failure modes (right) for specimens 1A (a), 3B (b), 4A (c) and 3A (d).

In Fig. 6(left), the responses of all the specimens in terms of load vs. stroke are set out and it is possible to appreciate that, up to failure, the scatter between the curves is very limited. This confirms that the tensile response of the fabric not embedded in the mortar is generally less stiff than the bond-slip mechanism.

In Table 1, the maximum loads reached in each test are depicted together with the occurred failure modes, underlying the differences with respect to the RILEM recommendations [11]. As shown in Fig.

7(left), it is interesting to notice that, except for the cases 2A and 3B, the maximum values of load reached by the different specimens resulted close to the average capacity of the plain FRCM composite under direct tension in the warp direction (9.13 kN). In case 3B, the early failure at the textile-to-matrix interface was probably related to a greater porosity of the mortar, Fig. 6(right-b), and a misalignment of the fabric with respect to the loading direction; in the 2A and the 3A cases, a cohesive debonding instead occurred, as shown in Fig. 6(right-d).

The recorded values of the slip measurement in the proximity of the peak loads were all close to zero, Fig. 7(right), confirming that all the surface finishes obtained by means of the hydroscarification process are adequate to the application of an FRCM reinforcement. Remembering the limited value of the anchorage length chosen for this experimental campaign, it appears that all the surface treatments might guarantee full exploitation of the FRCM capacity.

Table 1 Single lap shear test results: maximum loads and failure modes identification following the RILEM recommendations [11]

Specimen	Water pressure [atm]	P_{max} [kN]	Failure modes
SL_1A	200	9.04	Tensile failure of the textile out of the matrix + external matrix layer (partial) ejection *
SL_1B	200	8.85	Detachment at textile-to-matrix interface
SL_2A	500	7.66	Cohesive debonding in the substrate / Detachment at matrix-to-substrate interface *
SL_2B	500	9.14	Tensile failure of the textile out of the matrix + external matrix layer (partial) ejection *
SL_3A	1000	8.95	Cohesive debonding in the substrate / Detachment at matrix-to-substrate interface *
SL_3B	1000	5.12**	Detachment at textile-to-matrix interface
SL_4A	1500	9.52	Detachment at textile-to-matrix interface
SL_4B	1500	9.19	Tensile failure of the textile out of the matrix + external matrix layer (partial) ejection *
SL_5A	2000	10.56	Tensile failure of the textile out of the matrix
SL_5B	2000	10.30	Tensile failure of the textile out of the matrix

**different from the RILEM failure modes description*

***influenced by a non-parallel textile-load arrangement and porosity of the repair mortar*

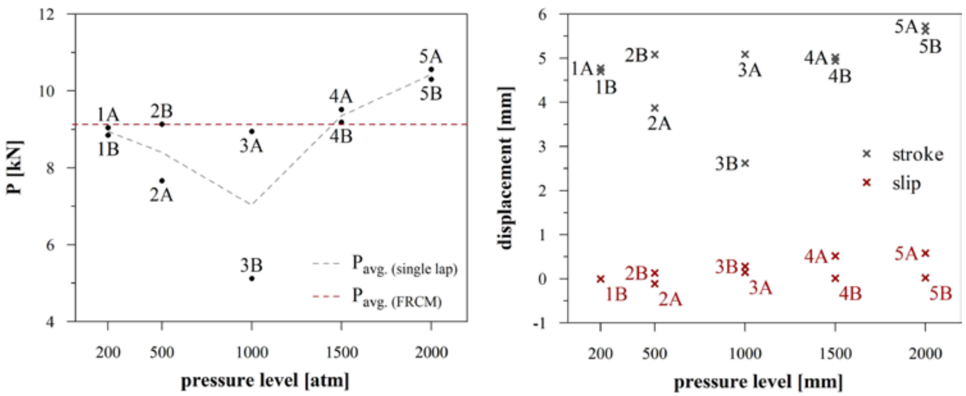

Fig. 7 Peak loads (left) and corresponding values of stroke and slip (right) for each single lap shear test. Please note that the SL_1A slip is not displayed due to the loss of the instruments during the test.

At the end, in Fig. 8, the responses of the two tests are displayed in terms of both stroke/slip vs. load. These graphs help to recognize the different failures occurred. In Fig.8 (left), the failure was reached by delamination of the FRCM layer from the support and the slippage value suddenly increased after reaching the maximum load capacity, while, in Fig. 8(right), the rupture of the AR-glass fabric took place, resulting in a slip value constantly close to zero throughout the whole test.

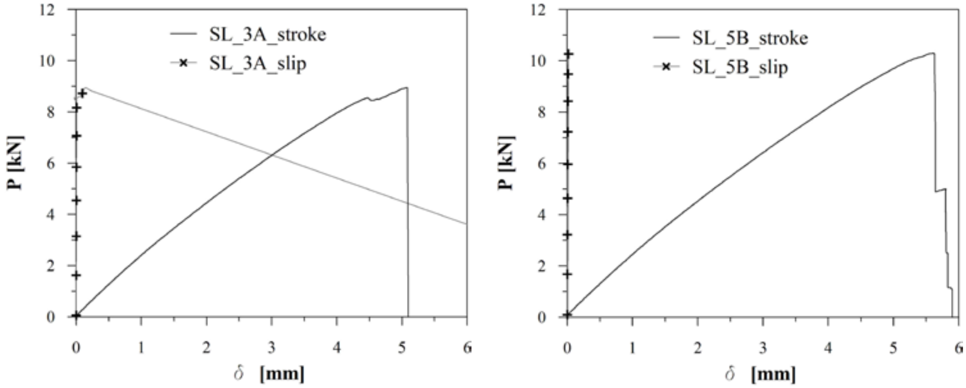

Fig. 8 Single lap shear test responses: load-stroke and load-slip curves for SL_3A specimen (left) and SL_5B (right). The failure modes are matrix-to-substrate delamination and textile rupture, respectively.

4 Conclusions and future developments

Based on the results of the experimental tests, it is possible to observe that, considering the limited anchorage length used, each pressure level imposed in the hydroscarification of the concrete substrate seems to be adequate to reach the minimum shear bond strength that guarantees the full exploitation of the FRCM reinforcement capacity. Please note that, in order to obtain the same results, the needed pressure level depends on the compressive strength and the granulometry of the concrete mixture.

Moreover, the good compatibility of the trends of the three proposed amplitude parameters with the increasing pressure level confirms that, by using this preliminary laser optical analysis, it is possible to adequately describe the roughness of the concrete substrates. This could be an important starting point in order to propose a simplified methodology to quantitatively characterize a surface profile before the application of an overlay reinforcement and to establish minimum roughness requirements for different repair mortars.

Furthermore, it is important to underline that the choice of a pressure level does not influence only the mechanical performance of the FRCM-substrate system, but also the cost of the application. In fact, to a greater level of roughness (hence pressure), an increase of the additional volume (i.e. additional material cost) of mortar required to restore the reference substrate surface before applying the FRCM system in its nominal thickness corresponds. The additional volumes and the corresponding increases in the overall retrofitting material costs (considering different nominal thickness values) are depicted in Fig. 9. This last analysis was carried out assuming to distribute the surface irregularity of the contact zone examined before on a square meter area, considering restoring the horizontal plane at the level of the maximum peak, R_P, and, to a first approximation, a cost of the base materials equal to 2000 €/m^3 for the repair mortar and 6 €/m^2 for the AR-glass fabric. Please note that in this preliminary computation the tolerance in the FRCM thickness is not considered.

In the upcoming experimental campaign targeting the full-scale response of retrofitted coupling beams, a hydroscarification pressure of 500 atm will then be used, in order to ensure sufficient bond also in the outer reinforcement regions. where delamination phenomena are likely to occur. Moreover, this choice allows containing the increase of the material costs under 4%, for all the considered nominal thicknesses.

Further developments regarding the study of the roughness-bond performance analysis might be related to the use of modified mortars with a better adhesion with the concrete surfaces (i.e. polymer-modified mortars) and to the creation of a groves pattern or the use of connector and mechanical anchors, in place of a global surface hydroscarification.

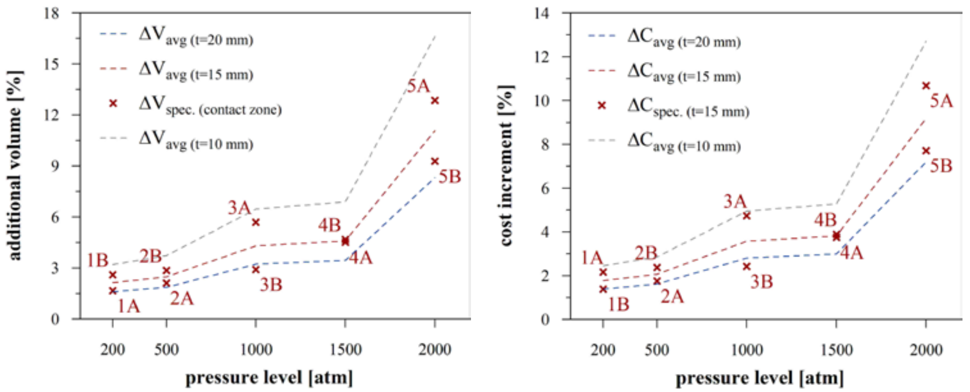

Fig. 9 Evaluation of the required additional matrix volume due to hydroscarification (left) and corresponding material cost increment (right) as functions of the investigated water pressures.

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