Strengthening of Masonry Structures under Compressive Loads by FRP Strips: Local-Global Mechanical Behaviour

M.R. Valluzzi, D. Tinazzi and C. Modena

Department of Constructions and Transportation Engineering
University of Padova, Italy

ABSTRACT

The study investigates the local and global aspects connected to the application of the "bed joint reinforcement technique" by using CFRP (Carbon-Fiber Reinforced Polymer) strips in compressed brick masonry walls. The intervention consists in embedding the strips into pre-cut mortar joints, and in refilling them with suitable mortar (lime-based). Results allowed defining the adhesion and the friction phases of the bonding phenomena and to characterize the anchoring effective length. Simulations on laboratory walls demonstrated the high effectiveness of the application when used for reduction of lateral dilation of cracked masonry. Mechanical, aesthetic and durability performances suggest the technique as very promising for historical masonry rehabilitation.

Key words: CFRP strips, masonry, bed joints reinforcement, compression, bond, pull-out tests.

INTRODUCTION

Existing masonry structures represent one of the most critical historical documents to preserve and exploit. They are an important symbol of our culture and any intervention on them has to take into account their historical identity; nevertheless, still today, in each phase of the restoration process, assessment, design and execution, there are insufficient indications and guidelines to refer to.

Historical masonry monuments (arch bridges, defensive structures, churches, bell towers, palaces) represent a typical case where the need of external confinement and particular aesthetic requirements are not compatible. In the specific field of the rehabilitation and strengthening of load bearing masonry structures, it is often necessary to operate with injections, substitutions, integrations and confinement rings. This last solution is traditionally performed by means of metallic members externally applied, which can produce, in some cases, aesthetics problems on masonry façades; moreover, the intervention does not effect any improvement of the mechanical properties of the material.

As reported in previous works /1, 2/, often in those constructions, some structural members subjected to over-stress due to long-term sustained loads, such as towers, curtain walls, arches and pillars, suffer creep phenomena caused by a continuous stress level even far from the ultimate compressive strength. The typical damage is revealed by thin cracks (but highly diffused and involving also the bricks) which can lead to unexpected collapses /3/.

In such a context, the bed joints reinforcement technique, at first employed using steel reinforced bars embedded into pre-cut horizontal mortar joints with suitable refilling mortars, has demonstrated his high reliability and aesthetic compatibility. It counteracts the propagation of the cracks thanks to the confining action of the reinforcement, which can carry the tensile stresses otherwise addressed to the bricks /1/. Tests are performed under monotonic or cyclic loads as the typical crack pattern is very similar to the effects of pseudo-creep simulations /2/. After experimental validation with laboratory tests the above technique has been applied successfully on monumental structures /4/.

In order to evaluate the effectiveness of highly specific, performance innovative materials for confinement, the technique, named also "FRP Structural Repointing", when involving epoxy mortar and FRP rods, was then developed and tested on damaged laboratory specimens made of brick masonry /5/.

Experiences cited in the literature mainly refer to application on reinforced concrete elements, focused on the study of the bond phenomena /6/, considering different surface conditions /7/, and for the calibration of proper analytical models /8, 9/.

Current research at Padova University has revealed that the use of CFRP strips (small plates having rectangular section and thickness around 1.5 mm) instead of rebars, allows less invasive applications, due to their more superficial placement and their greater adaptability to the possible joints unevenness. Consequently, the level of damage provoked on the original masonry is reduced, while corrosion problems are absent. Moreover, while direct comparisons on the ultimate bond and load capacity of specimens reinforced with steel and FRP rods is not possible, as in the cited researches different bricks and mortars were used, from qualitative analysis it is possible to assume that masonry panels reinforced with CFRP strips present a better global mechanical behaviour as a consequence of the lower influence of the strips in local splitting failures.

Finally, the contextual use of lime-based high performance mortars can allow FRP structural repointing to comply with material compatibility requirements, while the application reaches an optimal trade-off between mechanical, aesthetic and durability performances.

DESCRIPTION OF THE STRENGTHENING TECHNIQUE

The proposed strengthening technique is based on the insertion of FRP strips in the bed mortar joints previously cut for few centimetres and then refilled with a repointing material. Such a technique is particularly suitable to brick walls having regular courses of mortar; it exploits the confining action provided by the bars by counteracting the dilation due to the compressive loads.

The intervention is characterized by the following operative phases:

1) Removal of plaster or finishing from the surface, to check the masonry condition.
2) Cutting of bed mortar joints with a grinder; the depth of the slots depends on the designed maximum level of stress to be reached in the strips. It must be noted that neither all bed joints nor both faces of a masonry wall need to be involved in the application; each intervention requires specific design.
3) Accurate inspection of the masonry: it may be appropriate to inject some large voids or replace some bricks.
4) Removal of powder through compressed air, or water. In particular, water is recommended when mortar is adopted for repointing.
5) Placement of a first layer of repointing material, which should be accurately compacted; hydraulic lime-based mortars with appropriate mechanical performances are recommended for use. They should be selected in order to guarantee maximum compatibility (chemical, physical and mechanical) with the original materials; nevertheless, they might contain special additives to compensate the shrinkage during the hydration phase or to provide tixotropic behavior.
6) Placement of the reinforcing FRP strips. Placing of plastic spacers may be appropriate to separate the reinforcement from the surface of the bricks. Also, the use of more bars with smaller transverse dimensions rather then ones of higher size should be preferred; see Figure 1.
7) A final layer of repointing material should be applied to seal the horizontal joints and for aesthetic and homogeneity purpose; special sands or pigments can be used to obtain particular effects (Figure 1).

The proposed technique does not require particular skills and tools during application and can be performed quite easily and quickly; however special care is required when cutting, cleaning and repointing the bed joints /10/.

EXPERIMENTAL PROGRAM

Selection and characterization of the materials

The preliminary phase consisted of selecting and

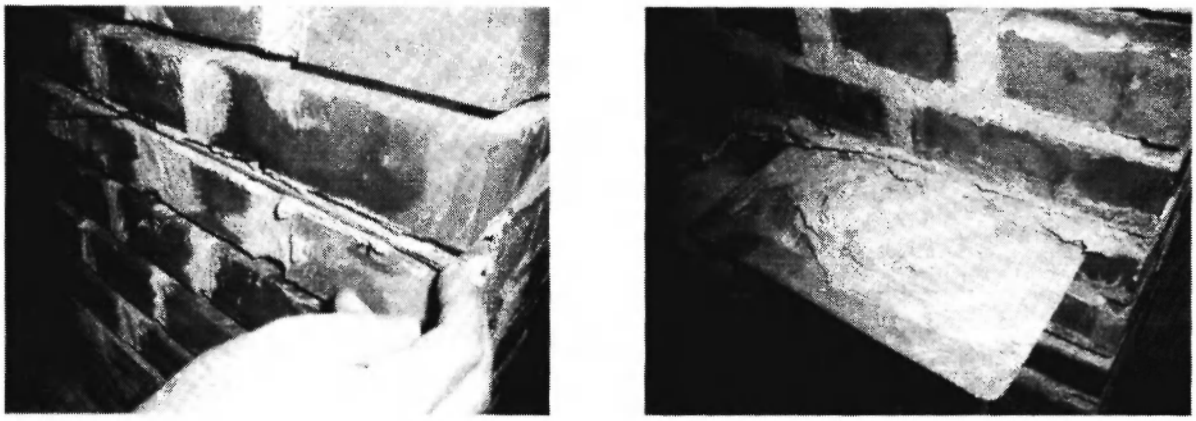


Fig. 1: Placement of the strip and repointing with mortar.

characterizing the most suitable materials to simulate the most diffuse masonry assemblages in Italy and to represent the most feasible strengthening applications based on FRP.

Bricks and mortar

The characterization of the masonry units is essential to determine and to explain the behaviour of the masonry assemblages. In the present research, as will be further explained later, it was necessary to investigate the behaviour of the interface between mortar and bricks as well. Common clay bricks were chosen for the experimentation, representing most of the masonry assemblages; the specific mechanical characteristics are summarized in Table 1. The test used for the brick characterization complies with the standards UNI 8942 1986. The type of hydrated lime mortar selected for the laying of the bed joints presents ordinary chemical and mechanical properties. In contrast, to exploit the high performances of the FRP reinforcement a high strength hydraulic lime mortar was selected for the repointing phase, that is for the filling of the bed joints after reinforcement is inserted into the superficial slots. The test used for the mortar characterization complies with the standards UNI EN 1015-11 1993. The characteristics of the used mortars are listed in Table 1 as well.

Table 1

Mechanical characteristics of the masonry units.

Property	Clay bricks	Laying mortar (28 days)	Repointing mortar (28 days)
Compressive strength [MPa]	17.24	10.32	15.61
Flexural strength [MPa]	6.40	0.63	0.83

Interfacial characteristics between mortars and bricks were determined through triplets tests applying different levels of stress orthogonal to the bed joints. Bond on mortar-brick interface is influenced by the orthogonal confining stress in accordance with the Coulomb theory, with angle of internal friction ϕ equal to 40.50 degrees and a cohesion coefficient c equal to 0.88. This type of test can well simulate the behavior bond between the mortar-brick interface in a real masonry assemblage subjected to compressive load.

CFRP strips

The type of the selected FRP reinforcement consisted of a pultruded strip (5 by 1.5 mm) externally sanded, made of carbon fibres embedded in an epoxy resin matrix.

That strip was a prototype tailored to the specifications we provided to the manufacturer on the basis of the previous researches carried out at the University of Padova, aimed to determine the optimal mechanical and geometrical properties for strengthening applications on masonry. In fact, compared to circular bars with equivalent area, thin strips are more flexible; therefore, they can better fit running irregularities of the bed joints. Moreover, the rectangular section also presents higher bond surface. The choice of carbon fibres was due to durability and creep immunity requirements. The drawback of the use of CFRP consisted in the high performances, typical of that composite material, which are excessive compared to the poor characteristics of masonry. In the specific case of the used prototype of strip, the type of carbon fibre and the fibre content were designed in order limit the modulus of elasticity and the tensile strength. The mechanical properties of CFRP strips were determined by direct tensile tests, obtaining an average value, over three specimens, of the modulus of elasticity equal to 73.2 GPa, while the ultimate tensile strength was equal to 1334 MPa, corresponding to an ultimate strain of 1.8%.

Local behaviour: Bond between CFRP strips and repointing mortar

Mechanisms of Failure

As is well known from the literature on bond of steel rods in concrete /6/, the possible mechanisms of failure are: splitting of the cover and pull-out of the bar. In case of FRP structural repointing, it is also necessary to take into account the brick-mortar interface and consider that all the repointing mortar prism can slide along the brick surface. In order to point out this phenomenon, the mechanisms of failure are therefore indicated here with splitting, sliding and de-bond (see Figure 2), where the latter refers to the detachment of the repointing mortar from the bricks.

The mechanisms of bond failures based on sliding of the strip into the repointing mortar are the most safe, as friction in the interface guarantees a pseudo-ductile behavior and can also be easily experimentally determined /11/.

From the preliminary work on material selection it was clear also that a further advantage that rectangular strips have on rods is their lower attitude in concentrating bond stresses along the thin sides, which helps to prevent premature failure due to splitting when they are horizontally led.

A special test setup was designed by the authors to determine how the parameter "*d*", depth of insertion of the strip, affects the bond by changing the mechanism of

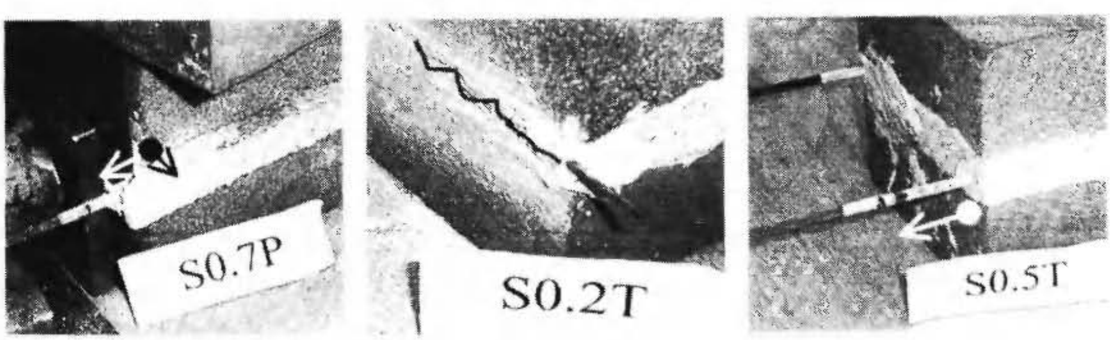


Fig. 2: Different mechanisms of bond failures: de-bond of repointing mortar, splitting on mortar surface, sliding of the strip into the repointing mortar.

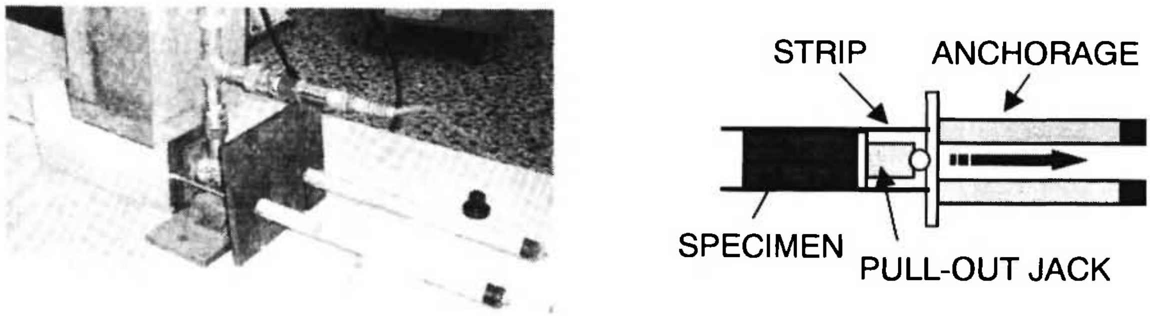


Fig. 3: Test specimen and setup scheme of the Pull-out vs. depth test.

failure. In addition, the possible different location, vertical or horizontal, of the strip into the bed joint, was investigated (the position is referred to the strip section: in Figure 2 it is vertical, while in Figure 3 it is horizontal). The test setup is represented in Figure 3, while results are reported in Table 2.

Table 2

Pull-out loads vs. depth test results.

	Insertion depth			
Position of the strip	d = 2 mm	d = 5 mm	d = 7 mm	d = 10 mm
Horizontal	-	5460$^{(1)}$	6070$^{(1)}$	6070$^{(1)}$
Vertical	5690$^{(2)}$	5910$^{(3)}$	6490$^{(1)}$	-

Units of loads are in N.
Failure modes: $^{(1)}$sliding, $^{(2)}$splitting, $^{(3)}$mortar de-bond.

Test results confirmed that a strip horizontally inserted tends to slide at any depth of installation, whilst a vertically inserted strips tends to behave similarly to a rod, presenting a de-bond mechanism related to the depth of insertion; specifically, a very brittle failure mechanism, due to splitting of the repointing mortar, occurs when the application is very close to the surface. At the minimum depth of 7 mm the sliding mechanism is guaranteed for both the strip configurations (vertical or horizontal) with a reasonable level of extracting load.

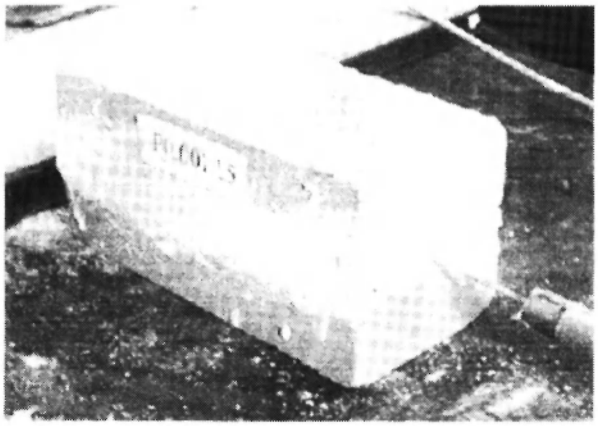
Pull-out tests

In order to collect essential parameters for design of a strengthening application, in addition to the mechanism of failure it is also necessary to determine the bond stress τ between the strip and the repointing mortar depending on the level of confining stress σ_t normal to the joint (axial load), which in a real application would be due to overloading of the masonry member after the intervention occurs.

Experiments refer to the pull-out test used for FRP bars embedded in concrete /12/, with some modifications: the axial load simulation was implemented with a constant confining stress orthogonal to the bed joint, while the strip was pulled out from the mortar joint with a hydraulic jack. One example of the specimens tested is represented in Figure 4; they were designed in order to prevent failures due to splitting in the brick or mortar but obtaining sliding of the strip. The adopted set-up made it possible to measure pull-out load and free-end slip while different levels of transverse stress are kept constant through a lateral actuator (Figure 4).

Four levels of confining stress (0.00, 0.25, 0.50 and 0.75 MPa) were chosen to simulate overloading from irrelevant to severe levels, see Table 3. Additionally, different anchoring lengths were introduced, in order to relate the pull out load with the anchorage length and the orthogonal stress. In standard pull-out tests /8/, the bond stress is given as an average value over the anchorage length, as it is obtained from the pull-out load over the anchorage surface (anchorage length by perimeter of the section).

As expected, tests revealed that pull-out load increases with the anchorage length and with the confining stress; the relation is almost linear for high levels of confinement (see Table 3), reaching a maximum value at 200 mm of anchorage and 0.50 MPa



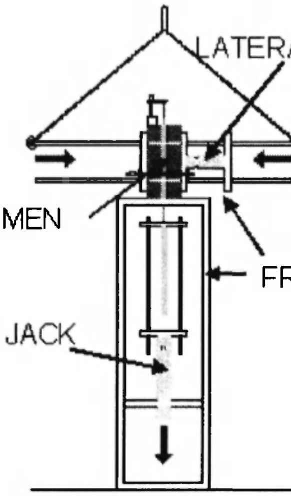


Fig. 4: Test specimen and setup scheme of the pull-out test with lateral confinement.

Table 3

Pull-out test results. Extracting load and average bond stress along the anchoring length.

Anchorage Length [mm]	*Confining stress levels*							
	0.00 MPa		*0.25 MPa*		*0.50 MPa*		*0.75 MPa*	
	Load [N]	*τ [MPa]*	*Load [N]*	*τ [MPa]*	*Load [N]*	*τ [MPa]*	*Load [N]*	*τ [MPa]*
20	988	3.8	1393	5.4	2669	10.3	2891	11.1
40	2763	5.3	3217	6.2	3325	6.4	4778	8.2
60	4547	5.8	4563	5.9	6882	8.8	n.a.	n.a.
75	5144	5.3	5466	5.6	6243	6.4	6716	6.9
100	6793	5.2	7025	5.4	n.a.	n.a.	n.a.	n.a.
150	6789	3.5	n.a.	n.a.	n.a.	n.a.	10886	5.6
200	9481	3.6	n.a.	n.a.	15174	5.8	n.a.	n.a.
250	9228	2.8	10981	3.4	n.a.	n.a.	n.a.	n.a.

of confinement, very close to the rupture of the strip. Additionally, it was possible to see that the average bond stress tends to increase with the anchoring length up to a certain length, beyond which, especially for low confinement, it decreases. That length tends to shorten when the confining stress increases, as can be seen in

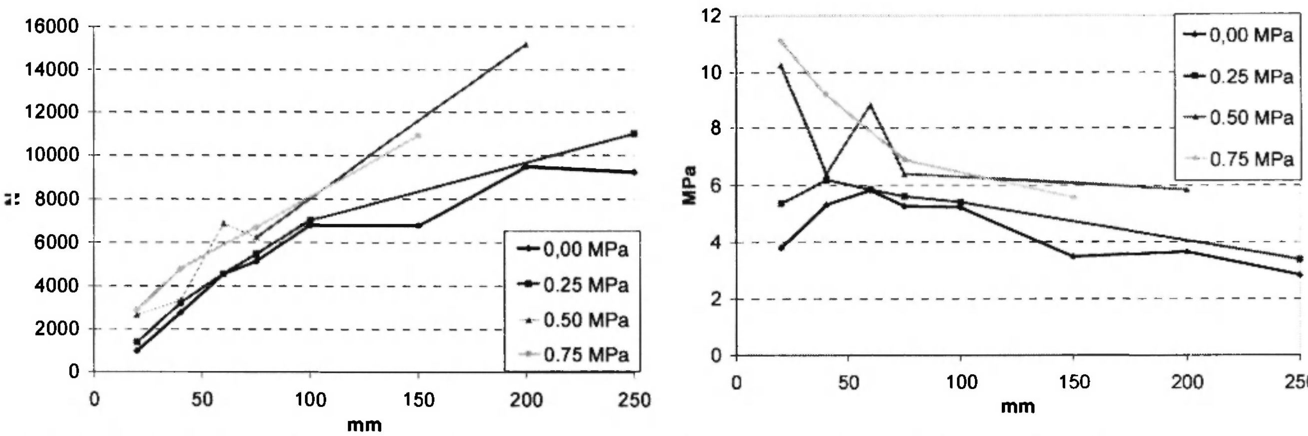


Fig. 5: Pull-out test results. Extracting load and average bond stress along the anchoring length at different confining stress levels.

columns of Table 3 and in the graphs of Figure 5, where the same results are depicted. In particular, it must be noted that some scattering of data around quite clear trendlines are probably due to particular interface conditions, such as aggregates pin action on the strip or the Achillides' effect /12, 13/, due to little geometrical variation of the strip section.

In particular, it was observed that for anchorage length up to 100 mm the transversal confinement does not significantly influence the pull-out load; while it has a crucial effect for longer anchorage lengths. Those results suggested that bond is related to different mechanisms, thus a new experimentation was designed.

Bond phenomena

Most of the current researches and guidelines on bond between FRP sheets and concrete define the development length or "Effective Length" as the minimum length required to reach the maximum anchorage capacity, while longer anchorage lengths do not ensure any further increase /12/; that is reached just before loss of chemical adhesion or substrate detachment, with a migration of the effective bonded area along the remaining anchorage. This means that not all the area considered for anchorage is actually involved by bond stress, but only the part named Effective Length.

When dealing with embedded rods, or strips, it has been observed that some residual bond remains in the detached areas due to friction in the strip-mortar interface /13/. Therefore, once chemical adhesion fails and de-bond propagates along the anchored areas, friction still guarantees a certain level of bond; of the two phenomena, friction is the one more influenced by transversal stress.

In order to determine the Effective Length and the load carried by adhesion or friction, six additional strain gauges were introduced on the previously described pull-out setup in order to measure local deformations along the strips.

Positions of extensometers on the strip and the length of embedment in the specimen are represented in Figure 6; a layer of protective glue completely covers the side where strain gauges are placed in order to totally exclude the influence on bond of that face of the strip; the anchorage length is equal to 200 mm.

It is feasible to think that, due to its particular section, the real behaviour of an embedded strip can be obtained by superposition, simply doubling the results of the single face anchorage.

Specimens are described in Table 4. Code P20_0 identifies a specimen with no confinement; label b, c and d are related to a repointing mortar weaker than the one used in all tests reported in this paper, due to an inappropriate mixing.

From equilibrium relations, gauges strain measurement were elaborated with equation (1) in order to obtain the bond- stress vs. position curves represented

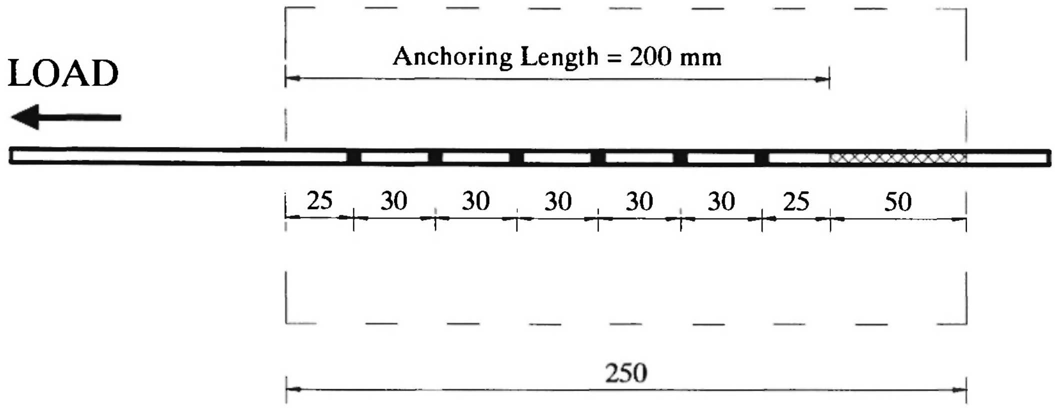


Fig. 6: Test specimen of the instrumented pull-out. Strain gauges position on the CFRP strip.

Table 4
Instrumented pull-out test results.

Specimen code	*Pull-Out Load [N]*	$\tau_{chemical}$ *[MPa]*	$\tau_{friction}$ *[MPa]*	*Load at chem. de-bond [N]*	*% of Pull-Out Load*	L_e *[mm]*
P20_0a	6930	10.1	6.8	4160	60%	134
P20_0b	2770	4.9	3.0	1660	60%	136
P20_0c	2430	4.8	2.8	n.a.	n.a.	125
P20_0d	2480	4.6	2.9	n.a.	n.a.	145
*P20_0,25**	3450	8.2	4.0	n.a.	n.a.	110
*P20_0,50***	5100	7.2	5.0	2550	50%	130

Transverse pressures: * 0,25 MPa; ** 0,50 MPa.

in Figure 7 /11/.

$$\tau(x_i) = \frac{1}{2}\frac{A}{p_e}E\left(\frac{\varepsilon_{i-1}-\varepsilon_i}{x_i - x_{i-1}} + \frac{\varepsilon_i - \varepsilon_{i+1}}{x_{i+1}-x_i}\right) \quad (1)$$

where:

τ is the bond stress;
x_i position of the gauges plus intermediate positions;
ε_i is the measured strain in position x_i;
A is the cross sectional area of the CFRP strip;
E is the CFRP strip modulus of elasticity;
p_e is the section perimeter involved on bond;

The graph in Figure 7 refers to specimen P20_0a at different levels of the pull-out load. It is possible to recognise the previously described propagation of the adhesion area once load reaches the 60% of ultimate; it was also possible to determine the peak adhesion stress, named $\tau_{chemical}$, the residual friction stress, named $\tau_{friction}$, and the effective length, L_e. The profile of the curve is triangular in the area where adhesion is present and pseudo-horizontal where friction remains. In Table 4 the main results of the six instrumented pull-out tests are summarized. Results confirm that both chemical adhesion and friction initially increase with transverse

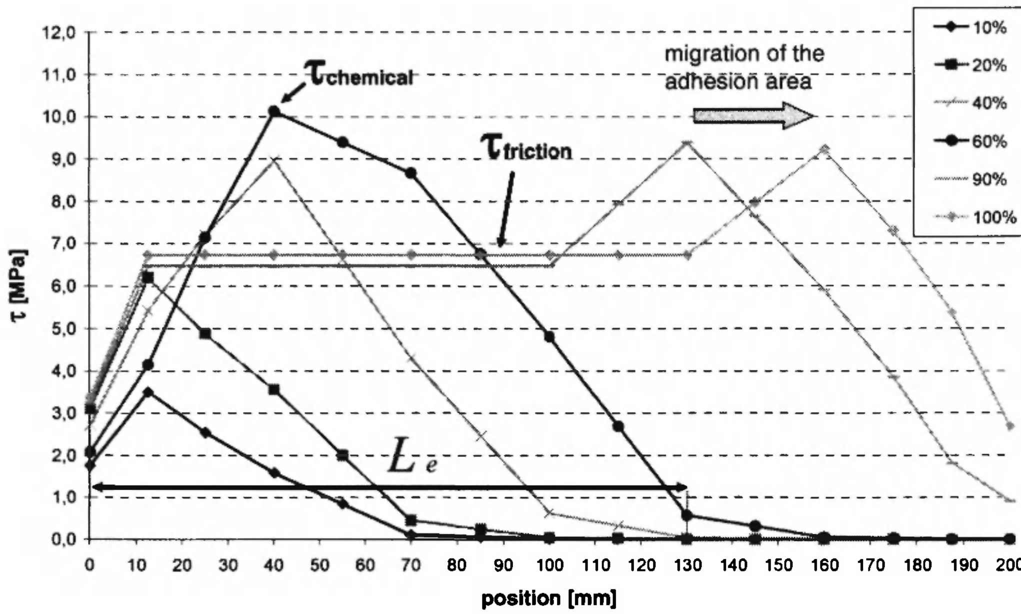


Fig. 7: Bond Stress vs. Gauge Position graphs at pull-out load increase.

stress; at least until this latter does not damage the interfaces.

The residual load bearing capacity, related to friction, is 40% of the ultimate load, still confirming a significant contribution; but most likely once detachment occurs, the residual bearing capacity is not stable, as an interfacial crack is present and, as a consequence, it would not be possible to rely on that anchorage for long term sustained loads. Another aspect to be considered is the step of cracks in already damaged walls once the FRP structural repointing technique is applied: the distance between two cracks must be lower than twice the Effective Length, otherwise adhesion bond stress could reach unsustainable levels and detachment would occur.

Both latter reasons underline the necessity for detailed knowledge of the bond phenomena on which design of anchorage details has to be based; hence, it is of relevance to perform pull-out test with internal strain measurement that can provide a detailed description of the local interaction of materials at different stress levels.

Results of the instrumented bond tests suggest the following considerations: as long as the anchorage length is shorter than the effective length, chemical adhesion prevails as bond mechanism and no significant differences are present at confinement variations. On the contrary, when a longer anchorage is available, the friction mechanism can occur; it prevails on the definition of the ultimate pull-out load and is responsible for the linear decay of the average bond stress. As is well known, friction increases with transversal stress much more than chemical adhesion; this explains why pull-out load increases with the confinement. As friction is a post-peak resisting mechanism, for anchorage design purposes the chemical bond stress has to be considered. As shown in Figure 2 and 4, on the surface of the extracted strip a thin layer of mortar is present; that is due to the fact that the strip surface is sanded and interlock occurs between sand grains of mortar and strip. This interlock effect is related to the surface preparation of the strip during manufacturing and it affects both the two mechanisms previously defined. As interlock effect is unclear, for the sake of simplicity herein it was comprised in the adhesion and friction mechanism. As a consequence, bond test results are obviously necessary any time a FRP strip presents a surface preparation which is different from the tested one.

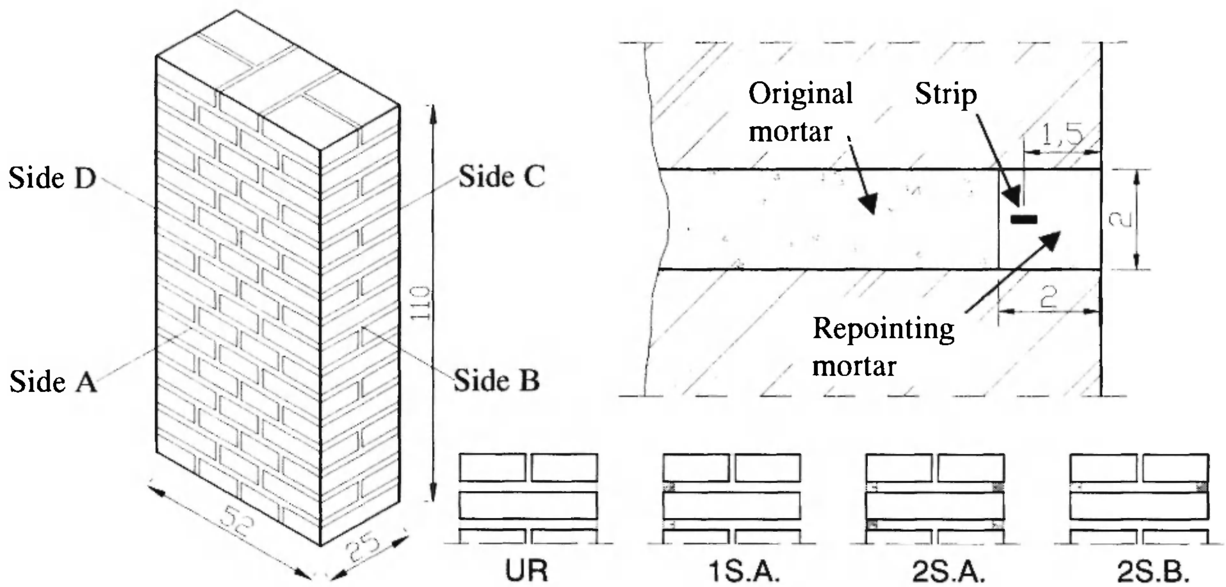


Fig. 8: Specimen dimensions (units are in cm). Detail of the reinforced bed joint. Reinforcement configurations.

Global Behaviour: Axial load tests on masonry specimens

In order to simulate the application of the strengthening technique on axially loaded masonry members and to develop analytical models for designing real scale applications, the research project also involved testing of seven coupon size walls.

The specimens to be tested are represented in Figure 8. The two-leaf masonry panels are 52x25x110 cm and present a typical texture of running bond clay bricks; they were tested under axial loads in the laboratory of Padova University. Four different strengthening configurations were designed for applying the CFRP strips into the mortar joints, see Figure 8 and Table 5. The depth of the strips was chosen based on the previously described tests, in order to prevent brittle failures in anchorage areas.

The average ultimate capacity of specimens UR.1 and UR.2 was used as reference for the reinforced ones; all specimens were tested up to failure. Results reported in Table 5 demonstrate that this technique, due to its low mechanical ratio of reinforcement, does not influence significantly the ultimate load and the modulus of elasticity, as their increments remain within the experimental scattering of results (note that 2S.A.2 present additional reinforcement: strips of common high strength CFRP sheet with wet lay-up application, see also Figure 11). In fact, the benefits of the technique are only oriented to the primary aim of the application, that is the limitation of cracks opening and propagation, due to sustained load. Then the effectiveness of the bed joint reinforcement with FRP thin strips can be evaluated referring to the reduction of the post-cracking lateral dilation /14/.

It must be considered also that a premature failure always occurred on the top of the specimens (see for example the inclined hatched bricks in samples 1S.A.2 Side C and 1S.B.1 Side A, in Figure 11), probably due to lack of confinement on the corners (as strips are not overlapped on the corners), see Figure 9; that certainly influenced the ultimate performances of the panels limiting the load capacity up to the brick splitting on corners. Specimen 2S.A.2 was thus over-reinforced with CFRP laminates having 0,165 mm of dry thickness, 1,5% of ultimate strain and Modulus of Elasticity equal to 230 MPa (Figure 11), in order to reach the maximum load capacity, which resulted almost 30% higher than the reference one.

Table 5

Specimen codes and test results: ultimate load, percentile increment of ultimate load on the average of the reference specimens, modulus of elasticity of the specimens.

Specimen code	*Reinforcement description*	*Ultimate load [kN]*		*% of increase on average of UR specimens*	*Modulus of Elasticity [GPa]*
UR.1	-	1402	Average: 1479	—	4982
UR.2	-	1556			8410
1S.A.1	Side A Each joint	1590		+7.5%	6024
1S.A.2	Side A Each joint	1612		+9.0%	4115
2S.B.1	Sides A,C Alternate joint	1695		+14.6%	7741
2S.A.1	Sides A,C Each joint	1365		-7.7%	7555
2S.A.2	Sides A,C Each joint	1884		+27.4%	4483

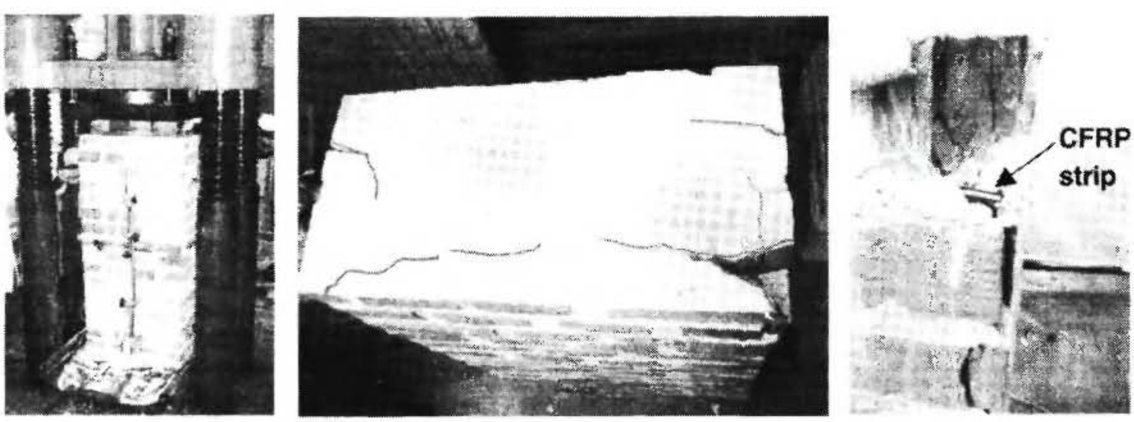


Fig. 9: Specimen under the hydraulic press (1000 tons). Specimen base typical failure pattern. Detail of the corner failure.

Measurement equipment consisted of eight displacement transducers (LVDTs) vertically and horizontally placed on the four sides of the panels; in addition, some strain gauges were bonded on the embedded FRP strips; a data acquisition system completed the instrumentation. Unfortunately, in some cases measurement instrumentation was removed shortly after cracking, to avoid damage, but that also prevented a comparison with the specimen's up-to-failure behaviour.

Table 6
Test results on panels: deformation and damage parameters.

CODE	*Ultimate Axial Stress [MPa]*	*Lateral Dilation (‰) at different Axial Stress Levels*						*1st Cracking*	
		2.5 MPa	*6.0 MPa*	*9.0 MPa*	*10.5 MPa*	*11.5 MPa*	*13.0 MPa*	*Axial Stress [MPa]*	*Lateral Strain [‰]*
UR.1	10.79	0.024	0.182	n.a.	n.a.	n.a.	n.a.	6.68	0.370
UR.2	11.97	0.024	0.083	0.218	2.468	3.646	n.a.	9.58	0.394
1S.A.1	12.23	0.023	0.086	0.436	n.a.	n.a.	n.a.	7.47	0.174
1S.A.2	12.40	0.046	0.149	0.634	1.519	2.574	n.a.	10.36	1.120*
2S.B.1	13.04	0.026	0.111	0.258	0.405	0.567	1.785	11.56	0.567
2S.A.1	10.50	0.016	0.132	0.450	1.195	n.a.	n.a.	3.85	0.042
2S.A.2	14.50	0.044	0.190	0.433	0.754	1.077	1.815	9.85	0.576

* Reinforced side only.

Table 6 shows lateral dilation levels recorded at relevant axial stress steps. Except when specifically noted, those reported are the average values on sides A and C of each panel. When reinforcement was present only on one side, unbalanced deformation between the opposite faces was recorded: on side A, the strengthened one of specimen 1S.A.1, a Poisson's ratio (between 30 and 60% of the ultimate load) equal to 0,13 was calculated; while the unreinforced face (side C) dilated with a Poisson's ratio equal to 0,37.

As can be seen in Figure 10, after cracking a relevant limitation of lateral dilation is obtained both for each joint and for the alternate joints strengthening configurations. In fact, at a stress level equal to 11,5 MPa (when the more relevant specimens are cracked) the dilation reduction in 1S.A.2 is equal to 45% of the reference panel UR.2; while specimens 2S.A.2 and 2S.B.1 reached a reduction equal to 70% and 85%, respectively.

The "alternate joints" configuration showed particularly effective results, if compared with the "each joint" one; this seems to be due to an excessive redistribution of micro cracks on the latter case, which caused lack of anchorage to the strips.

Results indicate that in case of damage due to sustained loads, the crack opening and propagation is limited, preventing in this way concentration of damage that could rapidly lead to collapse.

In Figure 11 crack patterns due to the different reinforcement configurations are reported: shadowed areas represent the distribution of micro-cracks, while major cracks are given in the picture. It is possible to observe that the reinforcement has forced a modification of crack patterns, enlarging it on the sides where strips are present; that is due to a stress redistribution that provides a better exploitation of the structural member. It must be noted that Side C of 1S.A.2 sample presents a pattern very similar to UR.2 and splitting cracks are very wide; as previously noted, that is the relevant effect of non symmetrical placing of the reinforcement on a two-wythes wall.

In panel 2S.A.1, except for the corners, no cracks are present; this was due to the fact that premature failure occurred at the corners before the inner part was involved by splitting cracks. This was confirmed by panel 2S.A.2, where the additional reinforcement has postponed the corner failure mechanism and joint reinforcement could bridge the vertical cracks. This

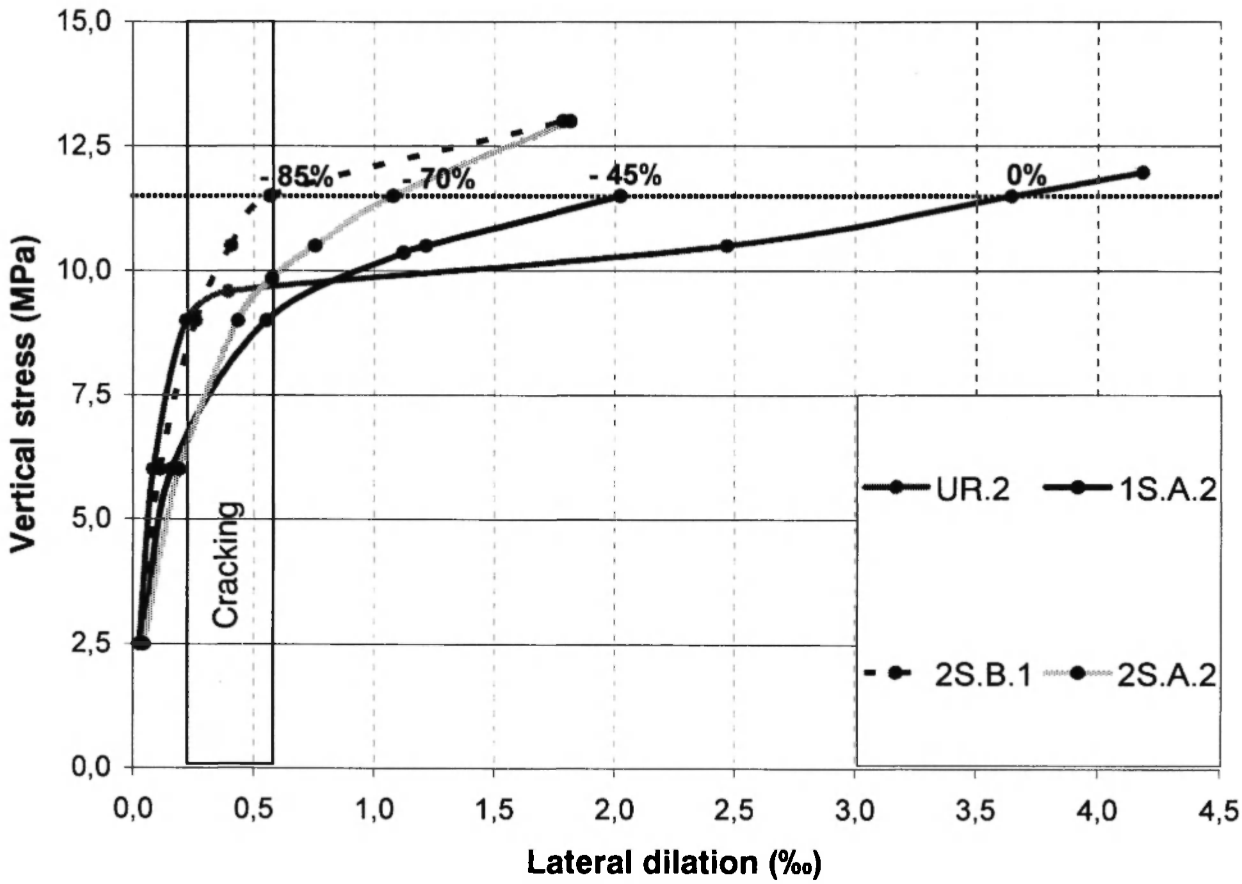


Fig. 10: Lateral dilation of some specimens at different axial stress levels, with the percentage reduction of lateral dilation at 11.5 MPa.

latter result suggested the need of manufacturing L-shaped strips for corner confinement and overlapping.

CONCLUSIONS

The experimental study on the masonry-reinforcement interfaces has demonstrated that the particular geometry of the CFRP strip makes it very suitable for bed joint reinforcement. At a certain depth of intervention brittle loss of anchorage is prevented and de-bonding mechanism involves adhesion as well as friction; both strength of mortar and axial stress remarkably influence the anchorage capacity and the effective length.

Instrumented pull-out tests, even if difficult to perform, can be successfully used to experimentally determine the evolution of the bond mechanisms and to quantify the relevant parameters.

Although the results on anchorage are consistent, further pull-out tests are needed in order to calibrate a precise bond model for the selected materials.

Tests on coupon size strenghtened specimens demonstrated that FRP structural repointing, when proper materials and configurations are selected, can be an effective technique for reduction of masonry lateral dilation due to cracking.

Although the geometry chosen for tested walls presented a premature failure on top of the specimens, that did not spoil the correct understanding of the behaviour of masonry assemblage, once border effects are disregarded. That suggests a positive implementation of the technique also on real load bearing masonry members.

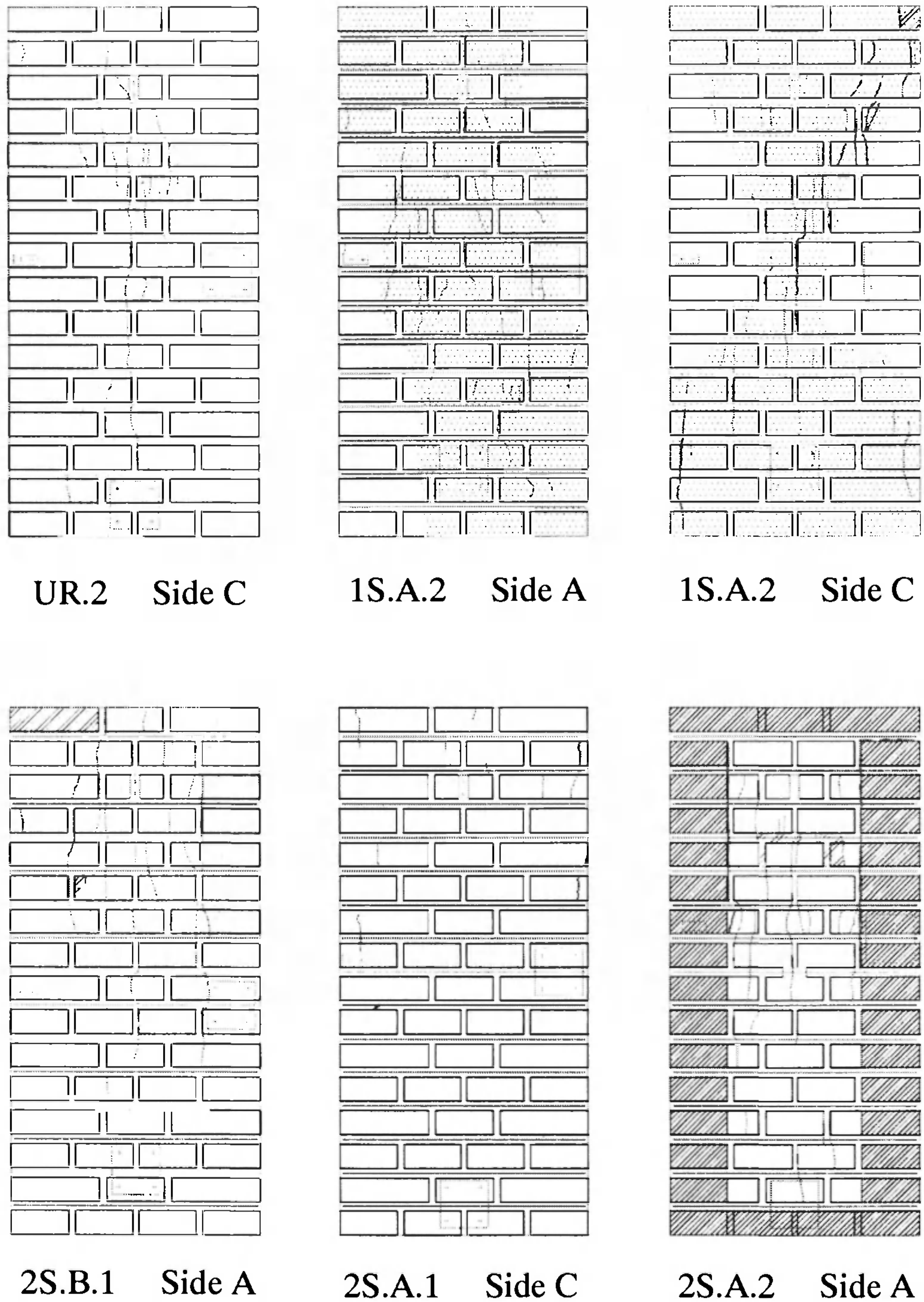


Fig. 11: Crack patterns of the tested panels. Areas where micro cracks are present are in dots hatches; deep cracks are in bold lines; very damaged bricks or mortar are in inclined hatch; only on specimen 2S.A.2 Side A inclined hatch on the perimeter represent external FRP sheets.

The development of the research is going toward testing of some damaged panels in order to simulate the application for repair of axially loaded masonry members once cracking has already occurred. The resulting effectiveness of the application will be related both to the axial stress and to the cracks average distance, in order to calibrate design models based on the anchorage capacity and the Effective Length, obtained by preliminar instrumented pull-out tests.

As previously mentioned, the proposed strengthening system also aims to limit masonry creep phenomena, typical of some monumental structures, due to long term sustained loads. To validate the system under this condition four more panels will also be subjected to predetermined cycles of axial loads to initiate creep. The preventive phase of investigation is already in progress, in collaboration with the Polytechnic of Milan.

Also on a local scale, the bond behaviour of FRP strips embedded in lime-based mortar subjected to long term loading is scheduled for investigation by means of a purpose-designed control system, which could also be used for performance monitoring of real scale applications.

The final aim of the whole research project is to develop, on the basis of the experimental experience, indications and design guidelines for the application of the proposed technique on real structures.

ACKNOWLEDGEMENTS

The present research was possible thanks to the fund "Young Researchers Project" - University of Padova, Italy. The authors would like to thank the company M.A.C. s.p.a. - DEGUSSA Group- of Treviso, Italy for the technical collaboration and the special support.

REFERENCES

1. L. Binda, C. Modena, M.R. Valluzzi and R. Zago, "Mechanical effects of bed joint steel reinforcement in historic brick masonry structures", *Structural Faults + Repair – 99*, 8th International Conference and Exhibition, London, England, July, 13-15, 1999 (CD-ROM).
2. L. Binda, C. Modena, A. Saisi, R. Folli Tongini and M.R. Valluzzi, "Bed joints structural repointing of historic masonry structures" *9th Canadian Masonry Symposium Spanning the Centuries*. Fredericton, New Brunswick, Canada, 4-6/06/2001.
3. A. Anzani, L. Binda and G. Mirabella, "The role of heavy persistent actions into the behaviour of ancient masonry", *Structural Faults + Repair – 99*, 8th International Conference and Exhibition, London, England, July, 13-15, 1999 (CD-ROM).
4. C. Modena and M.R. Valluzzi, "Repair techniques for creep and long term damage of massive structures", *STREMAH*, Haldikiki, Greece, 7-9 May 2003, C.A. Brebbia Ed., WitPress, UK, pp. 141-150.
5. D. Tinazzi, M. Arduini, C. Modena and A. Nanni, "FRP-Structural Repointing of Masonry Assemblages", *Advanced Composite Materials in Bridges and Structures*, 3rd International Conference, Ottawa, Canada, 15-18 August 2000., Ed.: J. Humar – A. Razaqpur, pp. 585-592.
6. R. Apinis, J. Modniks, V. Tamuzs and R. Tepfers, "Centric and eccentric pull-out tests for estimation of bond and splitting tendency of FRP reinforcement". Chalmers University of Technology, Division of Building Technology, Work No 31. Publication 99:3. Göteborg, 1999. p. 3. *Contribution to the XVII Symposium on Nordic Concrete Research*, 4th-6th August 1999, Reykjavik, Iceland.
7. C.E. Bakis, V.S. Uppuluri, A. Nanni and T.E. Boothby, "Analysis of bonding mechanisms of smooth and lugged FRP rods embedded in concrete", *Composites Science and Technology*, **58**, 1307-1319 (1998).
8. E. Cosenza, G. Manfredi and R. Realfonzo, "Behaviour and modelling of bond of FRP rebars to concrete", *Journal of Composites for Constructions, ASCE*, V**1** (2), 493-504 (1997).
9. L. De Lorenzis, and A. Nanni, "Bond between near surface mounted FRP rods and concrete in structural strengthening", *ACI Structures Journal*, **99** (2), 123-133 (2002).
10. M.R. Valluzzi, L. Binda and C. Modena,

"Experimental and analytical studies for the choice of repair techniques applied to historic buildings", *RILEM Materials and Structures,* **35**, 285-292 (2002).

11. M.R. Valluzzi, D. Tinazzi and C. Modena, "Bond of CFRP strips embedded in lime mortar", Proc. *Innovative Materials and Technologies for Construction and Restoration (IMTCR) 2004,* International Conference, University of Lecce, Lecce, Italy, June 6-9, 2004, pp. 70-80.
12. *fib* Task Group Bond Models, 2000. Bond of reinforcement in concrete – *State of the Art. Bulletin 10, fib.*
13. Z. Acchillides, K. Pilakoutas and P. Waldron, "Modelling of FRP bond behaviour", *Non-Metallic (FRP) Reinforcement for Concrete Structures, FRPRCS-3,* Sapporo, Japan, Vol. 2, JCI, 423-430, 1997.
14. D. Tinazzi, M.R. Valluzzi, N. Bianculli, F. Lucchin, R. Gottardo and C. Modena, "FRP strengthening and repairing of masonry under compressive load", Proc. *Structural Faults + Repair 2003,* Commonwealth Institute, Kensington, London, UK, 1-3 July 2003, (CD-ROM).