COMPRESSIVE BEHAVIOUR OF BRICK MASONRY PANELS STRENGTHENED WITH CFRP BED JOINTS REINFORCEMENT

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ABSTRACT
The study investigates the compressive behaviour aspects connected to the application of the bed joints reinforcement technique performed with CFRP (carbon fibre reinforced polymer) thin strips. The intervention technique can be particularly suitable in counteracting the typical damaging phenomenon of massive brick masonry structures, which is denoted by diffused thin vertical cracks (creep behaviour). The intervention consists in embedding the strips into pre-grooved mortar joints, and repointing them with a suitable hydraulic lime based mortar.
Experimental laboratory tests were carried out on selected materials constituting the wall samples (solid clay bricks and lime-based mortars) and the reinforcing materials. In particular, according to the requirements of durability, compatibility, low obtrusiveness, and structural performance optimization, a hydraulic lime-based mortar as embedding product and a flexible CFRP thin strip, having a rectangular cross section 5×1.5mm, were used.
In the paper, the results obtained by monotonic compression tests on brick masonry panels in plain, strengthened and repaired conditions after pre-damage are compared. Moreover, the main results of a series of laboratory pseudo-creep compression tests carried out on brick masonry panels strengthened with CFRP thin strips are presented and compared with those obtained from standard compression tests.

KEYWORDS: bed joints, brick, compression, CFRP, creep, masonry.

INTRODUCTION
Masonry structures constitute a very significant amount of the Architectural cultural heritage assets all over the world and their preservation and exploitation is often a critical issue. Studies carried out by the Politecnico di Milano since the nineties [1,2] showed that massive structures as towers, curtain walls, pillars, can be in critical conditions under constant heavy dead loads even for stress values lower than the strength of the masonry. This condition, which is related to the long term behaviour of masonry, can entail a sudden collapse in a relatively long time such that happened to the Civic Tower of Pavia [3] and to other cases. The long term behaviour can start even at 45-50% of the nominal strength value [4]. The experimental data did show an increase of

lateral deformations in time caused by the development of typical thin vertical cracks, crossing mortar bed joints and cracking bricks, due to compressive stresses. These results suggested that the evolution of the typical crack pattern, which can appear on the external walls of masonry buildings, should be carefully analysed [5]. In such a situation the development of the typical damage can be properly counteracted with the bed joints reinforcement technique, which consists in the introduction of reinforcing bars into the bed joint of the masonry [6]. The first research, performed in collaboration by the Politecnico di Milano and the University of Padua, concerned the use of small diameter steel bars, and allowed to perform some interventions on historic structures under hazardous conditions (e.g. St. Sofia church in Padua, the bell tower of the Monza Cathedral) [6,7]. In the last years, the attention was focused on the use of carbon fibre reinforced polymers (CFRP) as reinforcement, often used in combination with traditional mortars, to avoid compatibility problems. CFRP bars were considered due to their favourable mechanical and physical performances, such as high strength, low weight and corrosion immunity. Lately, thin CFRP strips were adopted in an experimental campaign at the University of Padova to strengthen or repair bed joints in clay brick masonry panels subjected to monotonic compression tests, by using the same reinforcing technique [8, 9]. Their thin rectangular section allows limiting the splitting phenomena during the loading phase in comparison with equivalent circular sections and makes possible more superficial applications, thus reducing the obtrusiveness of the intervention, as validated at the University of Padova by a large experimental campaign on the study of bond at local level [9]. The experimental campaign was then completed at the Politecnico di Milano by a series of accelerated creep tests on specimens with the same features and the same reinforcement configurations. These tests simulate long term conditions by incremental load steps kept constant for suitable intervals [5].

INTERVENTION TECHNIQUE

The bed joints reinforcement technique has demonstrated his effectiveness in the dilation control due to the cracking phenomena [6]. This goal is achieved by the insertion of reinforcing bars into mortar bed joints in order to bear the tensile stresses otherwise directed to the bricks and, consequently, to reduce the dilation of the wall. The main operative phases for a proper execution of the technique are widely reported in [6, 7, 8]. At first, stainless steel rebars were considered and embedded into horizontal mortar joints with suitable repointing mortars at every three brick courses [6, 10]. Laboratory experimental tests simulating both monotonic and creep loads, carried out on strengthened and plain masonry panels, showed a significant reduction of the lateral dilatation of about 37-39%. Moreover, a reduction of the crack pattern was also detected [6, 10]. A further development of the technique involved the use of CFRP rebars, in place of steel ones, and both lime-based and epoxy mortars. CFRP rebars were used in order to evaluate their effectiveness with compatible or high specific performance embedding products [11]. Results pointed out that the better performances were obtained with symmetric applications and that the use of high strength epoxy resins as embedding material can be inappropriate, due to the more brittle behaviour both at local and global level [11]. Current research at the University of Padova is focused on the use of CFRP thin strips, with a rectangular section of 5×1.5 mm (Figure 1a), because of their better mechanical performances and the possibility of more superficial applications (Figure 1b,c). This last reinforcement type is contextually used with hydraulic lime-based mortars. This allows for FRP-based structural repointing complying also material compatibility requirements. while the application reaches an optimal trade off between mechanical, aesthetic and durability performances [9].

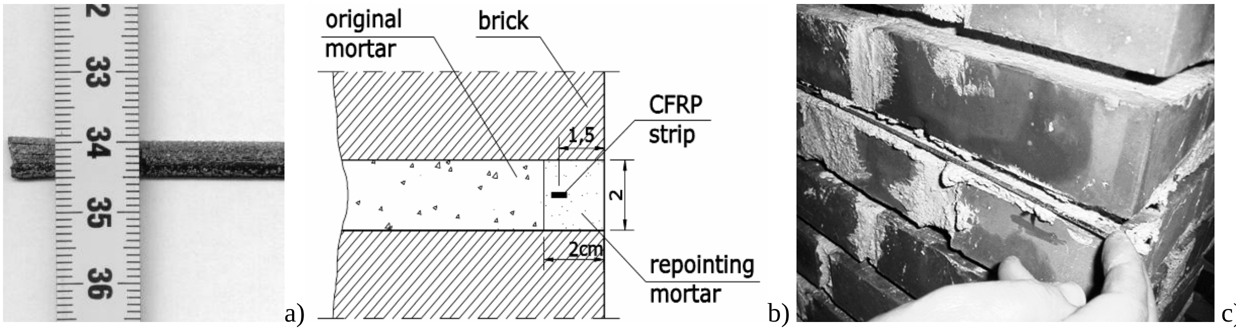


Figure 1: Bed joints reinforcement technique: a) CFRP thin strip, b) reinforcement positioning detail, c) insertion of a CFRP thin strip in a masonry panel

EXPERIMENTAL PROGRAM

In order to simulate the application of the bed joints reinforcement technique, performed with CFRP thin strips, an experimental program was carried out in collaboration between the University of Padova and the Politecnico di Milano. The effectiveness of CFRP thin strips in strengthening and repairing of masonry damaged by long term actions was studied.

A first phase of the research was performed at the University of Padova. Preventive selection and characterization of the basic materials were done in order to optimize the CFRP positioning configuration and a series of monotonic compression tests were carried out [8, 9, 12]. The second phase of the research was carried out at the Politecnico di Milano and was aimed at the evaluation of the long term behaviour of strengthened masonry by means of the execution of pseudo-creep compression tests [5].

The same materials were used in both research phases: a CFRP thin strips with a nominal rectangular cross section of 1.5×5.0 mm^2 and a sand coated surface, to enhance bond behaviour, having an ultimate tensile strength of 1445 N/mm^2, at a corresponding strain of 1.74%, and a modulus of elasticity of 80000 N/mm^2; solid clay bricks 250×112×55 mm^3 having a compressive and flexural strengths of 43.0 and 6.40 N/mm^2, respectively, and a modulus of elasticity of 16800 N/mm^2; an ordinary hydraulic lime mortar used for bed and head joints with a compressive and flexural strength after 28 days of curing of 10.1 and 2.6 N/mm^2, respectively, and a modulus of elasticity of 6400 N/mm^2; a high strength hydraulic lime mortar for the joint repointing having a compressive and flexural strength after 28 days of curing of 15.4 and 3.3 N/mm^2, respectively, and a modulus of elasticity of 9060 N/mm^2.

Monotonic and creep tests were carried out on plain, strengthened and repaired brick masonry panels. Two-leaf masonry panels 52×25×110 cm^3, with a Flemish bond arrangement of bricks, were used (Figure 2a). CFRP thin strips were inserted into repointed mortar joints of sides A and C (Figure 1b,c) according to four different reinforcement configurations (Figure 2a,b; Table 1).

In order to study the compressive behaviour, mainly of sides A and D, CFRP strips were always inserted in each bed joint of sides B and D to moderate the effects of cracking in the thickness. The preliminary monotonic compression tests carried out on these masonry panels highlighted a premature failure, usually concentrated at the top of the panels, due to the lack of reinforcement overlapping at the corners [12]. Due to the very innovative product no anchoring device was available at that stage to guarantee the proper bond at corners (in the next future, according to the results of the research, the production of L shaped element would be possible). Therefore, to prevent such a premature failure, high strength CFRP sheets were applied around the corners and

lateral sides of specimens 2S.A.2 and 2S.A.4 C (Figure 2b) to achieve the maximum compressive strength [5, 8, 12].
The measurement equipment consisted in several displacement transducers vertically and horizontally placed on the four sides of the panels and in a data acquisition system. In some cases the measurement instrumentation was removed shortly after cracking, to avoid damages. This prevented a full comparison of the behaviour of the specimen up to failure [5, 8].

Table 1: Matrix of the tests

Specimen	Load type	Intervention	Reinforcement description of sides A & C	Reinforcement ratio [‰]
UR.1	Two cycles	---	---	0.00
UR.2	Monotonic	---	---	0.00
UR.3 C	Pseudo-creep	---	---	0.00
1S.AS.1	Two cycles	Strengthening	Only side A, each joint	0.41
1S.A.1	Two cycles	Strengthening	Only side A, each joint	0.41
2S.B.1	Monotonic	Strengthening	Sides A & C, every two joints	0.44
2S.A.1	Monotonic	Strengthening	Sides A & C, each joints	0.82
2S.A.2	Two cycles	Strengthening	Sides A & C, each joints + CFRP sheets	0.82
2S.A.3 C	Pseudo-creep	Strengthening	Sides A & C, each joints	0.82
2S.A.4 C	Pseudo-creep	Strengthening	Sides A & C, each joints + CFRP sheets	0.82
UR.2.R	Monotonic	Repairing	Insertion in all sides of strips at each joint	0.82
1S.A.1.R	Monotonic	Repairing	Insertion in side C of strips at each joint	0.82

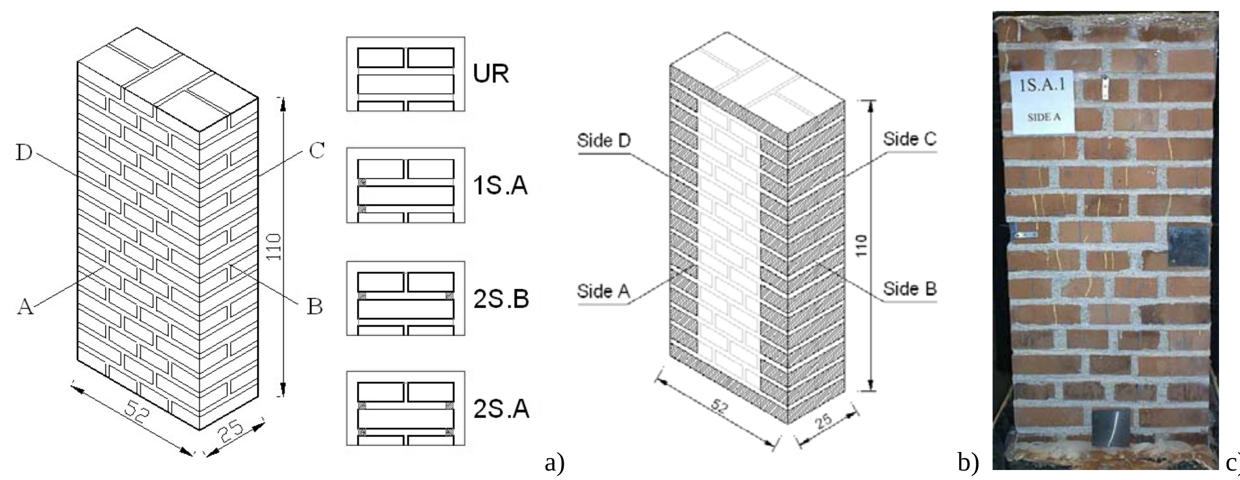


Figure 2: a) Masonry panels dimensions and reinforcement configurations; b) application of CFRP sheets around corners, c) specimen 1S.A.1 after compression test.

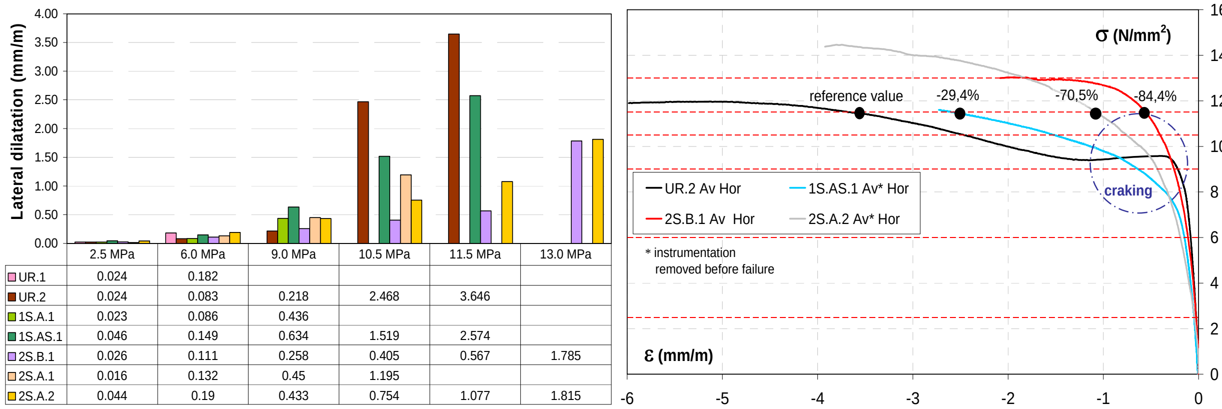
EXPERIMENTAL RESULTS OF MONOTONIC COMPRESSION TESTS
In Table 2 the main experimental results in term of ultimate loads, deformation and damage parameter are presented for strengthened masonry panels. Furthermore, in Figure 3 the lateral dilatations of the specimens are compared at different compressive stress levels in order to have a better insight of the efficiency, in counteracting the lateral dilatation, of the intervention technique. Average values of the unreinforced specimens were used as reference for the reinforced ones.

The results reported in Table 2 confirm that this technique, due to its low 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. 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. Moreover, the results of Table 2 showed a considerable limitation of lateral dilatation for both the each joint and the every two joints strengthening configurations. The horizontal deformations are reduced in a range of 40÷80% after the attainment of a compressive stress higher than that of first cracking of the unreinforced masonry panels. In particular, at a stress level of 11.5 N/mm^2 the lateral dilation reduction in 1S.A.2 is of 29%, while 2S.A.2 and 2S.B.1 reached a reduction of 70% and 84%, respectively (Figure 3). The symmetric alternate joints configuration, CFRP strips every two bed joints, of the specimen 2S.B.1 resulted particularly effective, if compared with the each joint one applied on the others masonry panels. Furthermore, the symmetric reinforcing configuration is more efficient than the asymmetric one in counteracting the lateral dilatation.
In Figure 4 crack patterns due to the different reinforcement configurations are reported. It is possible to observe that the reinforcement has forced a modification of crack patterns, widening it on the sides where CFRP strips are present; this is due to a stress redistribution that provides a better exploitation of the structural member. It must be noted that Side C (unreinforced) of 1S.A.1 sample presents a pattern very similar to UR.2 and wide cracks. This is the relevant effect of asymmetrical placing of the reinforcement. 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 cracks. This was confirmed by panel 2S.A.2, where the additional reinforcement postponed the corner failure mechanism and the CFRP strips could bridge the vertical cracks on sides A and C. This latter result can suggest that L-shaped strips, for corner overlapping, might be useful [8, 9].

Table 2: Test results on strengthened panels: deformation and damage parameters; between parentheses the variation in comparison with UR specimen is reported.

Speci-men	σ_u (N/mm^2)	$E_{30-60\%}$ (N/mm^2)	Lateral dilatation at σ_u (mm/m)	Lateral dilatation (mm/m)						1st cracking	
				2.5 (N/mm^2)	6.0 (N/mm^2)	9.0 (N/mm^2)	10.5 (N/mm^2)	11.5 (N/mm^2)	13.0 (N/mm^2)	σ_{cr} (N/mm^2)	Lateral deform. (mm/m)
UR.1	10.79	10375	---	0.024	0.182	---	---	---	---	6.68	0.370
UR.2	11.97	9737	5.12	0.024	0.083	0.218	2.468	3.646	---	9.58	0.394
1S.AS.1	12.40 (+9.0%)	7722 (-23.2%)	---	0.046 (+91.7%)	0.149 (+12.5%)	0.634 (+191%)	---	---	---	10.36 (+27.4%)	1.120 (+193%)
1S.A.1	12.23 (+7.5%)	7001 (-30.3%)	---	0.023 (-4.2%)	0.086 (-35.1%)	0.436 (100.0%)	---	---	---	7.47 (-8.1%)	0.174 (-54.5%)
2S.B.1	13.04 (+14.6%)	7829 (-22.2%)	1.85 (-63.9%)	0.026 (+8.3%)	0.111 (-16.2%)	0.258 (+18.3%)	0.405 (-83.6%)	0.567 (-84.4%)	1.785	11.56 (+42.2%)	0.567 (+48.4%)
2S.A.1	10.51 (-7.7%)	5459 (-45.7%)	1.19 (-76.8%)	0.016 (-33.3%)	0.132 (-0.4%)	0.45 (106.4%)	1.195 (-51.6%)	---	---	3.85 (-52.6%)	0.042 (-89.0%)

2S.A.2	14.50 (+27.4%)	5379 (-46.5%)	---	0.044 (+83.3%)	0.190 (+43.4%)	0.433 (+98.6%)	0.754 (-69.4%)	1.077 (-70.5%)	1.815	9.85 (+21.2)	0.576 (+50.8)



	2.5 MPa	6.0 MPa	9.0 MPa	10.5 MPa	11.5 MPa	13.0 MPa
UR.1	0.024	0.182				
UR.2	0.024	0.083	0.218	2.468	3.646	
1S.A.1	0.023	0.086	0.436			
1S.AS.1	0.046	0.149	0.634	1.519	2.574	
2S.B.1	0.026	0.111	0.258	0.405	0.567	1.785
2S.A.1	0.016	0.132	0.45	1.195		
2S.A.2	0.044	0.19	0.433	0.754	1.077	1.815

Figure 3: (left) Comparison of lateral dilatation of the strengthened specimens at different compressive levels; (right) lateral dilatation of some specimens with percentage variation at the compressive stress of 11.5 N/mm^2.

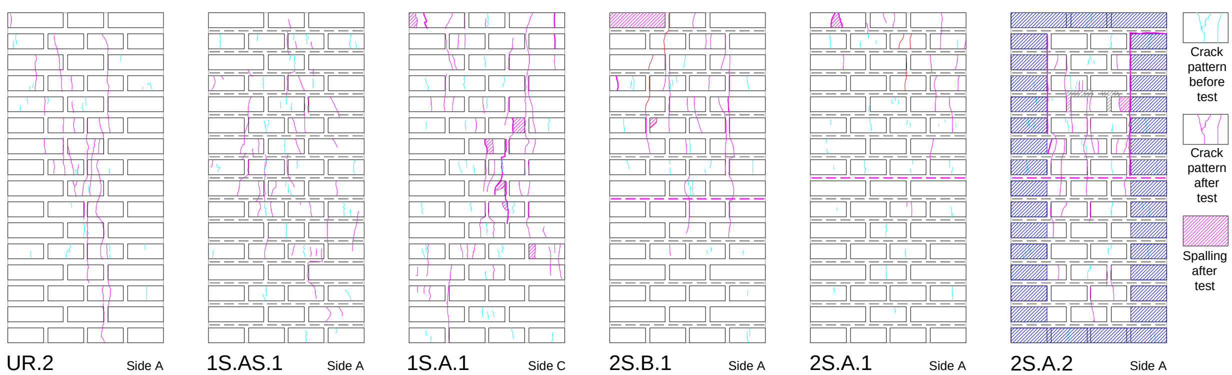


Figure 4: Crack patterns of some strengthened masonry panels after standard compression test. Only for specimen "2S.A.2 - Side A" inclined hatch on the perimeter represents external CFRP sheets.

Unexpectedly, both repaired specimens UR.2.R and 1S.A.1.R revealed a noticeable performance: the axial stiffness was recovered and the first cracking stress was reached again. This means that cracks occurred after the first test could not freely propagate as it would happen, even at negligible axial stress levels, when loading failed plain masonry. Moreover, the repaired specimens were able to bear load up to the former cracking stress with reasonable vertical and horizontal deformations [12]. The repaired masonry panels have shown similar crack patterns than the former ones. Repaired long sides A and C were further damaged by a growing of the existing cracks and by the appearance of new cracks. In these two masonry panels, CFRP sheets were not used at the corners as reinforcement overlapping. Therefore, as for some strengthened specimens, wide cracks appeared at the corners [9].

EXPERIMENTAL RESULT OF PSEUDO-CREEP COMPRESSION TESTS

Accelerated pseudo-creep tests on strengthened masonry panels were carried out [5]. The results and the collapse mechanisms led to point out some specific aspects of the compressive behaviour of the strengthened masonry panels.

Table 3: Test results on repaired panels: deformation and damage parameters; between parentheses the variation in comparison with reference specimen is reported.

Speci-men	σ_u (N/mm^2)	$E_{30\text{-}60\,\%}$ (N/mm^2)	Lateral dilatation at σ_u (mm/m)	Lateral dilatation (mm/m)				1st new cracking	
				6.0 (N/mm^2)	8.0 (N/mm^2)	9.0 (N/mm^2)	10.0 (N/mm^2)	σ_{cr} (N/mm^2)	Lateral deform. (mm/m)
UR.2	11.97	9737	5.12	0.083	0.140	0.218	2.006	9.58	0.394
UR.2.R	10.09 (-15.7%)	7818 (-19.7%)	0.99 (-80.6%)	0.370 (+354%)	0.619 (+342%)	0.745 (+242%)	0.914 (-54.5%)	2.92 (-69.5%)	0.056 (-85.5%)
1S.A.1	12.23	7001	---	0.086	0.231	0.436	---	7.47	0.174
2S.A.1.R	9.62 (-21.3%)	7077 (+1.08%)	1.27	0.795 (+823%)	1.176 (+410%)	1.719 (+293%)	---	4.62 (-38.2%)	0.558 (+220%)

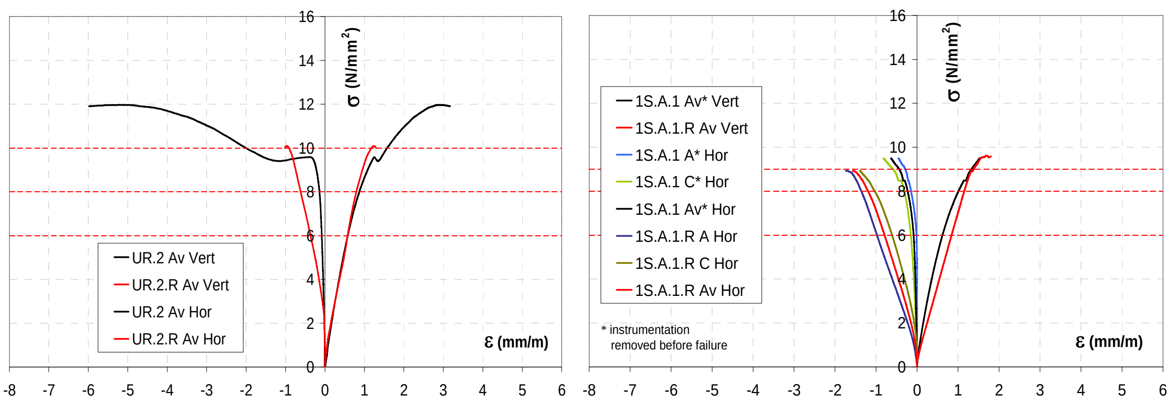


Figure 5: Comparison of lateral dilatation of the repaired specimens, (left) UR.2 versus UR.2.R and (right) 1S.A.1 versus 1S.A.1.R.

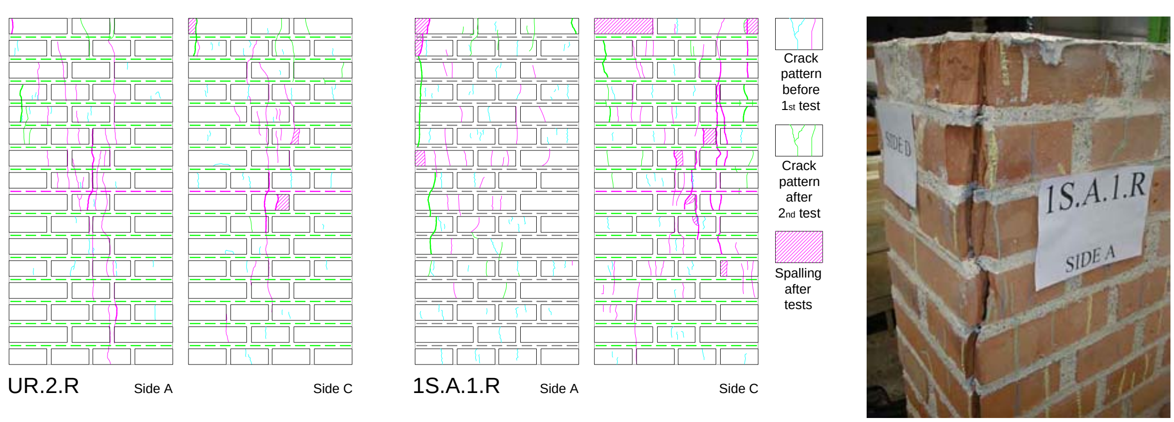


Figure 6: Crack patterns after test of repaired panels (left), and corner detail (right).

In agreement with the previous standard compression tests, the ultimate behaviour of the masonry panels is not affected by the reinforcement (Figure 7). The recorded lateral

deformations versus time and stress are shown in Figure 8. Regarding the horizontal deformation the results showed a lower lateral dilation for strengthened panels (Figure 7). Nevertheless, the 2S.A.4.C test results were affected by the failure mechanism of the corner CFRP sheet detachment, as happened for 2S.A.2 specimen. This local failure interfered with the horizontal transducers (Figure 7), making unfeasible the comparison between the three specimens at peak load. The compressive failure mechanisms were similar to those detected during monotonic tests. It was possible to notice how the presence of reinforcement in the short and in the long sides moved the concentrated splitting failure from middle axis of the short sides, unstrengthened test, to the rupture of the corners. Therefore, to turn this mechanism in the cracking of the main sides (A and C) with diffused cracks, the effective confinement at the corners by connection of the reinforcement was needed. The connection was again performed with an external overlapping made with CFRP sheets.
Crack pattern similar to those of reinforced masonry panels subjected to standard compression test were obtained. The unreinforced panel UR.3.C showed larger deformation in the shorter sides (Figure 9a). The prevalent damages in the short sides, B and D, are along the symmetry axis. In order to prevent this type of failure, CFRP strips were again inserted in the bed joints. Nevertheless, the reinforced panel 2S.A.3.C appears more cracked, with wide expulsions and spalling of the external parts of the bricks (Figure 9b). The crack pattern, in fact, does not interest anymore the central part of the short sides but it is concentrated in proximity of the corners (Figure 9b). In general, it can be supposed that the geometry and the distance between the strips can influence the mechanism of failure, as also pointed out in [9]. Moreover, the use of the CFRP bed joint reinforcement leads to a noticeable transverse deformation of a superficial layer of masonry, which is likely due to the different modulus of elasticity of bed and repointing mortars as pointed out in [9]. The sample 2S.A.4.C, as expected, showed diffused cracks in the main sides A and C but, despite the crack pattern was less serious than the other panels, its failure happened very suddenly due to the peeling of the CFRP sheets (Figure 7and Figure 9c).

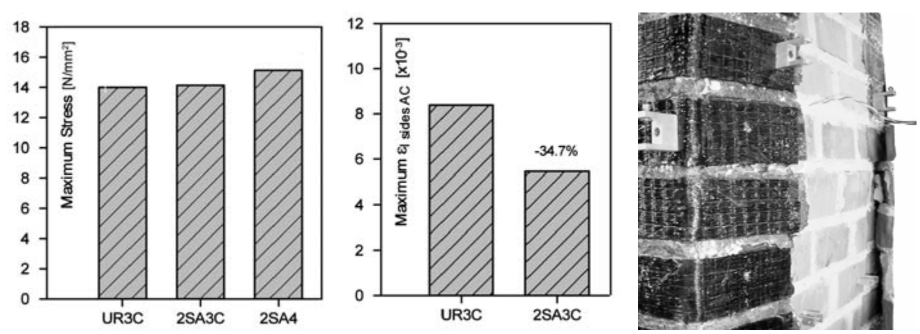


Figure 7: Maximum compressive stresses (left), and maximum horizontal deformations measured in the accelerated creep tests (centre). Test 2S.A.4.C: the CFRP sheet detachment interferes with horizontal transducers (right) [5].

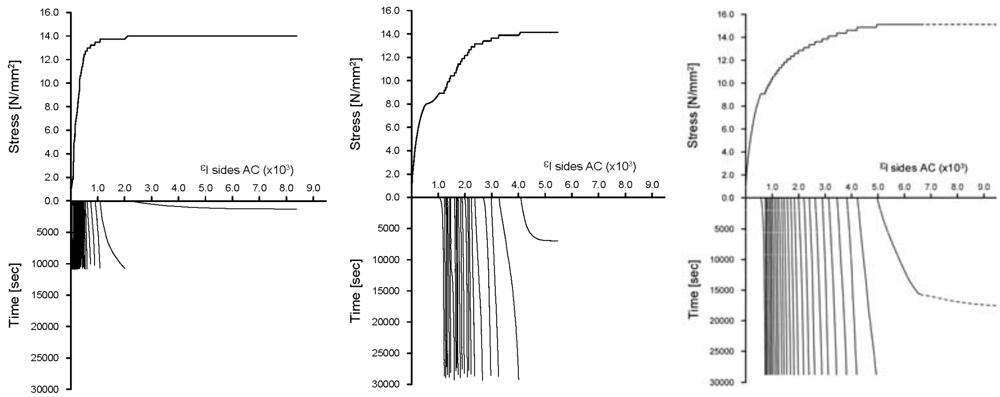


Figure 8: Compressive stress and time vs. horizontal deformation of sides A and C of the specimens UR.3.C (left), 2S.A.3.C (centre) and 2S.A.4.C (right) [5].

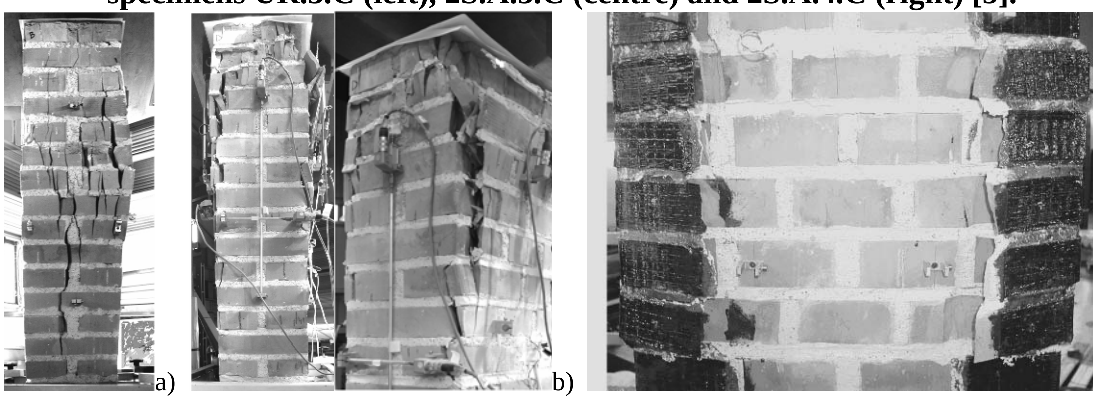

a) b) c)

Figure 9: a) Crack pattern of the specimen UR.3.C, b) crack pattern of 2S.A.3.C with material spalling, c) crack pattern of 2S.A.4.C with peeling of CFRP sheet [5].

CONCLUSIONS

In the paper, an experimental study on the compressive behaviour of masonry panels strengthened and repaired with the bed joints reinforcement technique using CFRP thin strips embedded in a hydraulic lime-based mortar has been presented. The experimental results on monotonic compression tests demonstrate that the insertion of small amounts of reinforcement, when proper materials and configurations are selected, can be an effective technique for counteracting the masonry dilatation due to cracking. Furthermore, this technique does not influence significantly the ultimate load and the modulus of elasticity of the original masonry. The insertion of CFRP thin strips can be made either in sound or damaged members (as cracking that have to be prevented or controlled from degenerating can be due to potential or active actions), thus providing effective strengthening or repairing interventions. The insertion of CFRP strips every two bed joints, resulted particularly effective, if compared with the each joint one. An interesting strength increment (+14%), together with a remarkable reduction of the lateral dilatation up to 80%, were obtained. Accelerated pseudo-creep tests on strengthened brick masonry panels confirmed that, likewise in the standard compression tests, the use of CFRP reinforcement does not influence the strength of the masonry and yields to a reduction of the lateral deformation of about 35% for the use of CFRP thin strips embedded at every joint of each side. This proves the suitability of the bed joints reinforcement technique, made with CFRP thin strips, in counteracting the peculiar damage occurring in massive masonry structures under constant heavy dead loads.

Therefore, this innovative system has a high potentiality for possible application on real cases. Nevertheless, several aspects still need to be deepened, as they can induce possible additional weakness in the masonry: the border effects due to lack of connection at the corners, the different modulus of elasticity between bed and repointing mortars, the feasibility on highly damaged structures, when the CFRP strips spanning between the sides of cracks acts as dowels, which is a critical behaviour due to the fragility of FRP under bending or shear loads, etc.
A further test program is in progress in order to better clarify the local behaviour at the interfaces among materials. Moreover, the possible application of specific L-shaped anchorages for corner overlapping of reinforcement in different geometrical conditions is going to be investigated. The final aim of the whole research is to develop, on the basis of the experimental experience, instructions and design guidelines for the application of the proposed technique on real structures.

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