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Repair techniques for creep and long-term damage of massive structures

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Abstract

In the paper, the main results of experimental researches carried out in recent years on the characterization of the bed joints reinforcement technique are presented. The technique is particularly effective for repair and strengthening of overstressed massive structures such as towers, curtain walls, pillars, etc. which can suffer, during their service life, creep and long-term damage. Several experimental studies have been conducted aimed to select the most proper materials (reinforcement, mortars) and to characterize the masonry in the strengthened and/or repaired situation. In particular, the use of reinforced stainless steel and of innovative CFRP (Carbon Fiber Reinforced Polymer) has been considered as reinforcement elements. As for the repointing, a large range of materials have been studied: hydrated lime and hydraulic lime-based mortars, additived or fiber-reinforced mortars and epoxy resins. Results have been compared in terms of global mechanical performances of the masonry but also in connection with many of the further significant aspects involved, as: feasibility of the technique, easy execution, compatibility with original materials, durability, aesthetics. Finally, some in-situ applications performed on historic buildings or structural components are briefly described.

Introduction

Studies carried out by the Polytechnic of Milan in the last decade [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.

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In such a situation the development of the typical damage, represented by thin and diffused cracks, can be properly counteracted by the introduction of reinforcing bars or plates into the bed joint of the masonry (bed joint reinforcement or structural repointing technique) [3].
In the last years several experimental works have been performed in collaboration by the University of Padova and the Polytechnic of Milan, aimed to characterize the new technique and to validate the possible application in the restoring of existing masonry building [4] [5]. Monotonic, cyclic and creep simulating tests have been carried out on masonry samples in different reinforcement configurations (one or both sides), and by using different repointing mortar (hydraulic lime or different types of additived mortars). Low diameter stainless steel bars were firstly adopted as reinforcing materials.
New experimental campaigns considering the use of innovative materials (pultruded bars or strips made of CFRP) are now in progress. In particular, carbon FRP components have been selected for their corrosion and creep immunity; their use, in fact, combined with suitable repointing materials can assure the proper durability of the intervention and, consequently, the retrofitting of the structural performance of the masonry.
In the paper the main results of the laboratory researches, performed on brick masonry panels strengthened by reinforcing circular section bars, are discussed. In particular, the comparison among the first applications, concerning the use of steel rebars, and the more recent ones, performed by fiber reinforced materials, is proposed. The experimental results allowed to calibrate a numerical model able to simulate different design conditions (spacing and amount of the bars) which allowed to detect the stress distribution in the original and strengthened configurations.
Thanks to the experimental and numerical validation, the technique has been already executed in several existing buildings during the last years, for the time being as regards the application of steel reinforcing bars. Some examples are: the pillars of the St. Sofia Church and the bell tower of the St. Giustina Basilica (both in Padova, Italy), the belfry of the Tower of Vicenza (Italy). An extensive intervention is now in progress on the Bell Tower of the Cathedral of Monza (Italy).
At moment, deeper investigations of the performances of FRP components (bars and strips, in particular) applied in combination with proper repointing materials are in progress, in order to check their advantages in substituting steel reinforcing elements in real cases interventions.

2 Experimental characterization of the technique

2.1 Tests program and materials properties

Figure 1 shows the geometrical scheme of the panels in the strengthened condition. Different configurations (both sides or just one reinforced) and different types of repointing material (hydrated lime and pozzolana mortars, also additived with fibers, hydraulic mortar, also additived with resins, or resins)

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were considered. The mechanical properties of the original and repointing materials are given in Table 1, whereas the general scheme of the tests program is given in Tables 2 and 3, both for stainless steel and CFRP bars.
The panels were tested under repaired or strengthened (i.e. without any previous damage) conditions, in order to simulate various in-situ detectable situations. Different loading conditions were also applied: monotonic, accelerated creep [5] or cyclic.
According to numerical simulations calibrated on the first experimental results (monotonic series) [6], which allowed to optimize the design of the intervention (spacing and number of the bars) in order to minimize the pre-damage of the masonry still maintaining the proper mechanical performances, the technique was applied every three mortar joints. Stainless steel bars 6 mm in diameter and pultruded CFRP bars 5 mm in diameter were adopted. Carbon FRP bars were characterized by tensile strength and elastic modulus equal to 2300 MPa and 130 GPa respectively, an ultimate strain of 1.8 % and a density of 16000 kg/m^3. Mechanical properties of the stainless steel were similar to FeB 44 k type.

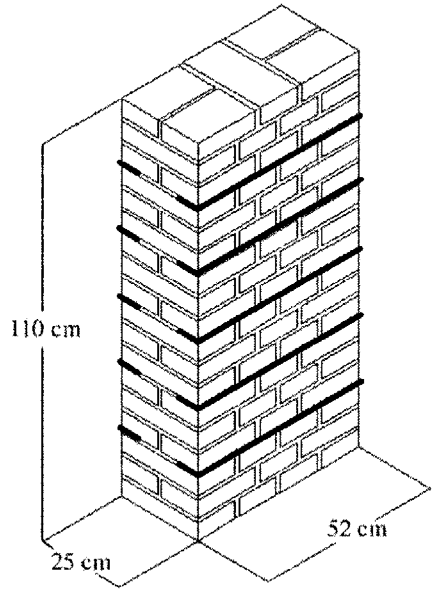

Figure 1: Geometry of the panels and reinforcing scheme.

Some phases of the execution of the techniques are shown in Figure 2. In the repaired panels mortar joints were excavated up to 5-7 cm using common tools, whereas in the strengthened ones recesses were pre-formed in the building phase. Then, after cleaning with compressed air (in case of resins used as repointing material) or water (for common lime-based mortars), a first layer of refilling material was applied. It has to be properly pressed in order to assure the suitable

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bond with the reinforcement. After lodging the bars, a final layer of pointing is applied and pressed against the reinforcement.

The proposed technique did not require particular skills and tools during application and was performed quite easily and quickly.

Figure 2: Execution of the technique: insertion of the bars and refilling of the excavated joints.

Table 1. Mechanical properties of the adopted materials.

Material	Compressive strength (MPa)	Elastic modulus (MPa)
Bricks	26.87	2470
Original Mortar	2.50	665
Hydrated lime and pozzolana mortar	4.78	4500
Hydraulic lime mortar	5.40	3890
Hydraulic lime mortar with resin	38.60	-
Fiber-reinforced hydrated lime and pozzolana mortar	16.72	15500
Resin type 1	50-90	4000
Resin type 2	55-65	6000-9000
Resin type 3	82	-

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Table 2. Experimental program: panels strengthened with stainless steel bars.

Series	Sample	Loading test	Intervention	Reinf. material	Repointing material
0-SS (unreinforced)	M01	creep	-	-	-
	M03	creep	-	-	-
1-SS (one side reinforced)	MU6H1	monotonic	repair	2Ø6	Hydraulic lime mortar
	MU6H2		repair	2Ø6	Hydraulic lime mortar
	MU6H3		repair	2Ø6	Resin type 1
	MU6H4		repair	2Ø6	Resin type 2
	MU6H5		repair	2Ø6	Resin type 1
	MU6H6		strength.	2Ø6	Hydraulic lime mortar
2-SS (two sides reinforced)	M02	creep	strength.	2Ø6	Hydrated lime and pozzolana mortar
	M04	monotonic	strength.	2Ø6	Hydraulic lime mortar with resin
	M05	monotonic	strength.	2Ø6	Hydrated lime and pozzolana mortar
	M06	creep	strength.	2Ø6	Hydraulic lime mortar with resin

Table 3. Experimental program: panels strengthened with CFRP bars.

Series	Sample	Loading test	Intervention	Reinforcing material	Repointing material
0-CFRP (unreinf.)	UR.1	monotonic	-	-	-
	UR.2	2 cycles	-	-	-
1-CFRP (one side reinforced)	1S.M.1	monotonic	strength.	1Ø5	Fiber-reinf. hydrat. lime & pozz. mortar
	1S.M.2	2 cycles	strength.	1Ø5	Fiber-reinf. hydrat. lime & pozz. mortar
	1S.R.1	2 cycles	strength.	1Ø5	Resin type 3
	1S.R.2	3 cycles	strength.	1Ø5	Resin type 3
2-CFRP (two sides reinforced)	2S.M.1	2 cycles	strength.	1Ø5	Fiber-reinf. hydrat. lime & pozz. mortar
	2S.M.2	3 cycles	strength.	1Ø5	Fiber-reinf. hydrat. lime & pozz. mortar
	2S.R.1	2 cycles	strength.	1Ø5	Resin type 3
	2S.R.2	3 cycles	strength.	1Ø5	Resin type 3

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2.2 Tests results and analysis

The experimental results obtained on panels repaired and strengthened with stainless steel bars subjected to monotonic or creep loads (series SS in the Table 2) are more extensively reported in [4] and [6], respectively. Nevertheless, some main aspects are here reprised, in order to better compare the results obtained on the panels strengthened with CFRP bars.

As for the repaired panels (monotonic series), due to the limited dimension of the samples in comparison with a whole existing wall, the damage caused by the cutting of the joints in the post-compression phase was in most cases excessive. Thus, it was not possible to re-establish the original strength of the plain panels (around 6.20 MPa). On the contrary, the most significant results were obtained in terms of reduction of the vertical crack pattern and, consequently, in the dilation of the masonry. In particular, for the adopted reinforcing configuration, a reduction of the tensile stresses in the bricks of about the 40% was estimated [4].

Despite expectable results, also in the strengthened series (tested both under monotonic and creep loads) the main role of the reinforcement was in the control of the horizontal deformations, rather than in increasing the strength of the masonry (maximum rate of 25%). In particular, as for the creep tests, the tertiary creep conditions were achieved in the strengthened panels around deformations of about the 70% higher than in the original case [5].

In both cases (repaired or strengthened series) the panels repointed with lime-based mortars showed the highest performances, both in terms of execution of the technique and of mechanical properties.

The most recent phase of the research, aimed in characterizing the structural potentiality of CFRP bars in the application of the bed joints reinforcement technique, confirmed that the best results are obtained for symmetric reinforcement (both sides) and for the use of lime-based mortar (Figures 3 and 4).

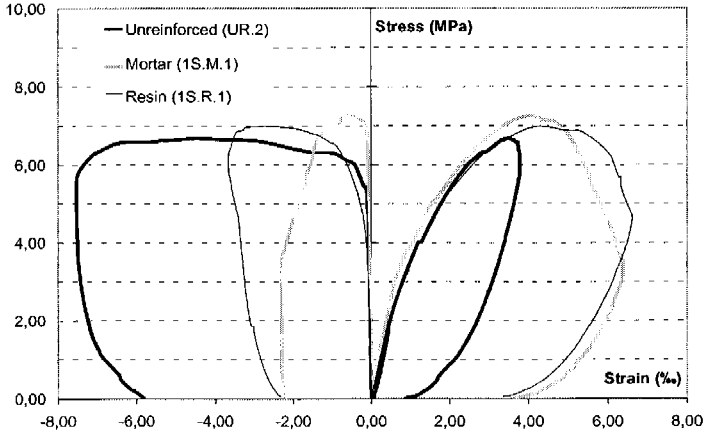

Figure 3: Stress-strain diagrams for 1-CFRP series (one side strengthening).

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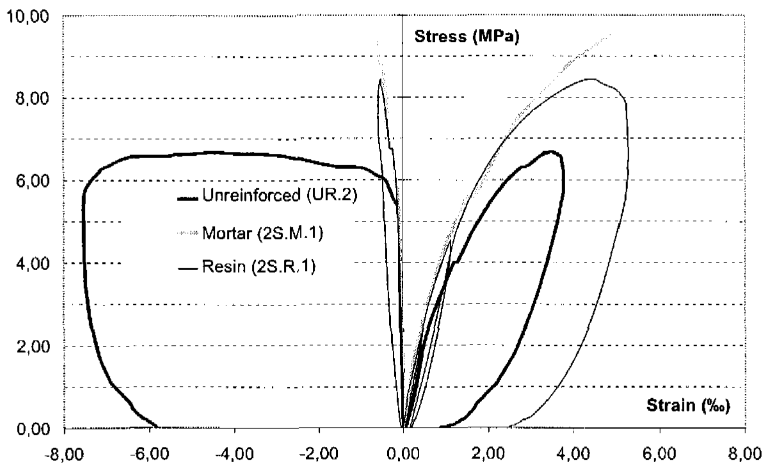

Figure 4: Stress-strain diagrams for 2-CFRP series (two sides strengthening).

The maximum increase in strength was around the 40% (2S.M panels), with a slight increase in the modulus of elasticity too. A great reduction of the crack pattern was detected at the end of the tests on the reinforced sides of the strengthened panels in comparison with the plain ones (decrease of the Poisson ratio of about the 50%) (Figure 5).

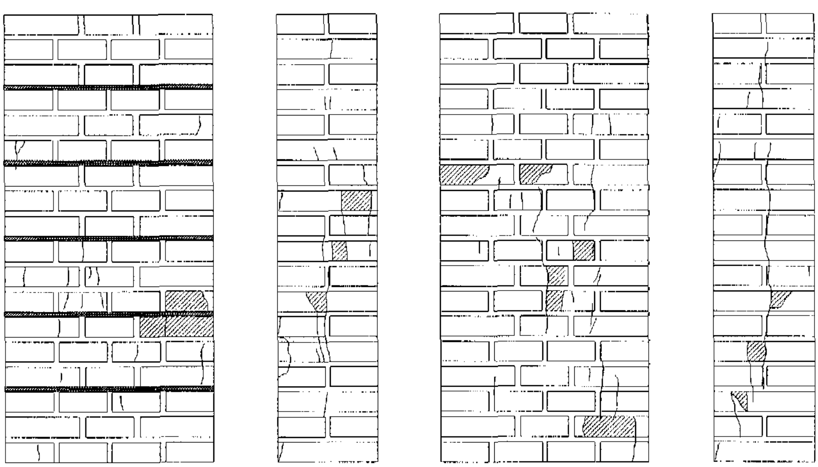

Figure 5: Final crack pattern for 1-CFRP series (one side strengthening).

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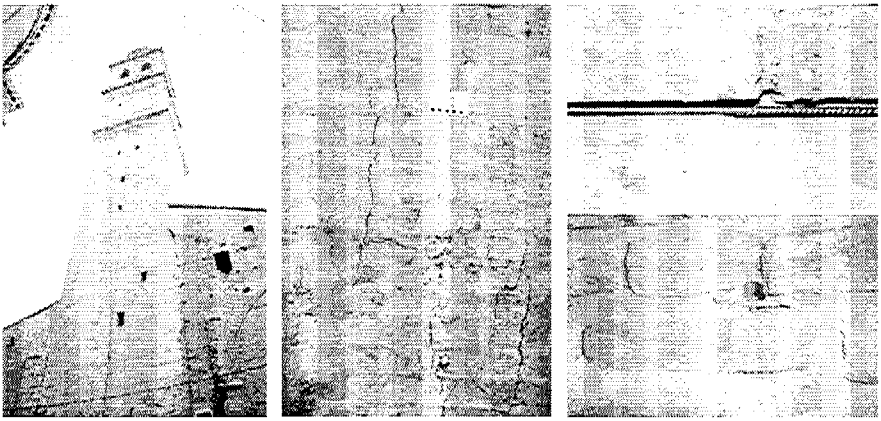
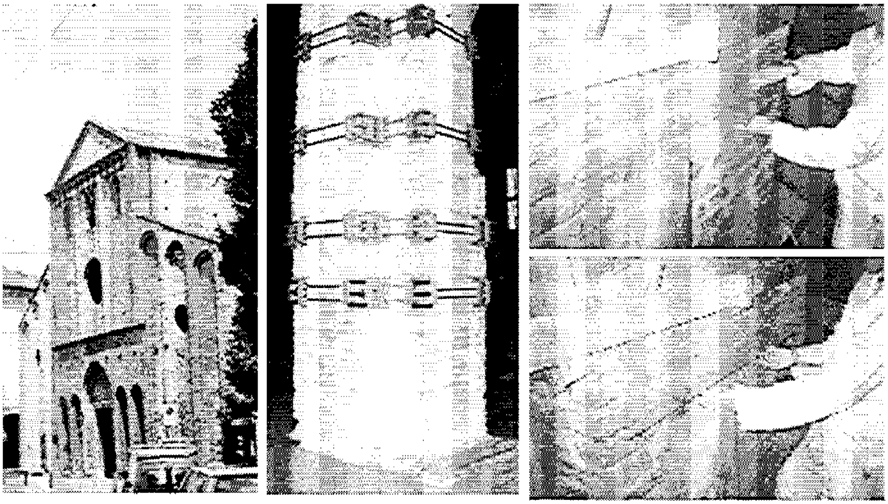
3 Case studies

Several in situ applications of the proposed techniques have already performed in some overstressed existing structures in Italy (Figure 6, 7 and 8). At the moment they are concerning the use of reinforced stainless steel bars (in combination with lime-based repointing mortars).



(a) (b) (c)

Figure 6: St. Giustina bell tower (Padova): general view (a), typical creep crack pattern (b), application of the technique (c).



(a) (b) (c)

Figure 7: St. Sofia church pillars (Padova): general view of the church (a), provisional measures on a cracked pillar (b), application of the technique (c).

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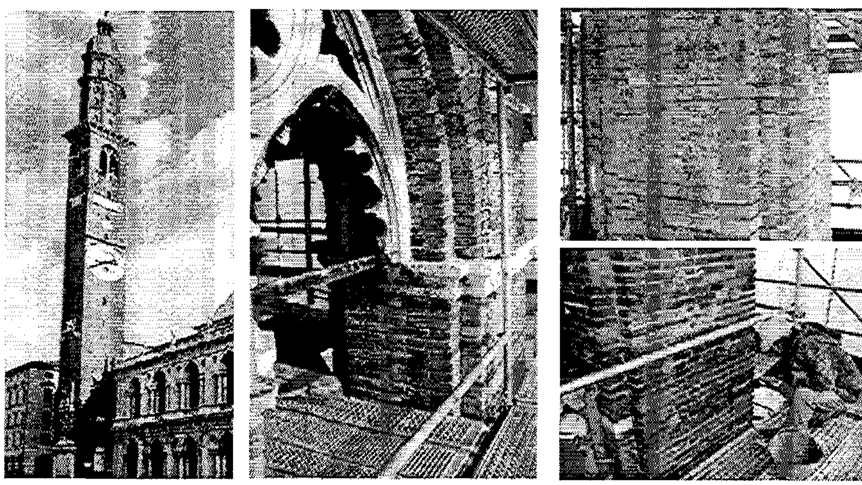
As demonstrated by the laboratory experience, both in repair and strengthening conditions, the bed joints reinforcement technique is easily and quickly performed; moreover, aesthetic aspects of the façade can be improved or maintained, depending on the specific conservation requirements.
In real applications, for the best efficiency of the intervention, is often required to insert some pins (s. Figure 6.c) through the masonry, especially when high thickness and multi-leaf structures are present. Moreover, in some particularly high damaged cases, the combination with injections or partial and local rebuilding can be executed (s. Fig. 7.c).



(a) (b) (c)

Figure 8: Civic tower of Vicenza belfry: general view (a), cracked pillar of the belfry (b), joints strengthened by structural repointing and combination with injections (c).

4 Conclusions

The bed joints reinforcement technique can be properly employed to counteract the typical damage caused by long-term compressive sustained loads. Experimental researches firstly carried out on the use of stainless steel reinforcing bars allowed to validate the adoption of the technique for several case studies. New experimental campaigns are now concerning the use of CFRP reinforcing elements (bars and strips, in particular). CFRP small diameter bars demonstrated they high efficiency, especially when combined with lime-based mortars as filling material, which have also higher compatibility (chemical, physical and mechanical) with the original constituents of the existing masonry.
Recent experimental studies, still in progress at the University of Padova, are particularly focused on the characterization of the local behaviour at the interface of the constitutive materials. First results showed that CFRP thin strips (5 by 1.5 mm), compared with CFRP bars (having equivalent area) have a better local

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behaviour, avoiding brittle splitting failures due to the higher bond surface and their lower attitude in concentrating bond stress along the thin sides. Moreover, they allow very low invasive applications, with lower pre-damage of the masonry during the execution phase, due to their more superficial placement and the more adaptability to the possible joints unevenness. This new reinforcing system seem to be particularly promising and effective for real in-situ applications, where an optimal trade-off among feasibility, mechanical, durability and aesthetics aspects is required. To the possible validation, both monotonic and creep simulating compressive tests are planned to be performed in collaboration with the Polytechnic of Milan.

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