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Durability Evaluation of Strengthening Mortars Applied to Historical Masonry Structures

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ABSTRACT

The restoration of historical masonry buildings is a complex process, in that the choise of the most compatible strengthening material compared to the original masonry plays a basic role for the durability of reinforced structures. The purpose of this study is to develop a methodology to be used in laboratory tests as a preliminary design stage for selecting a durable strengthening mortar. Through static and fatigue tests on different dimensional reinforced masonry specimens it has been possible to investigate their long-term behaviour, in order to select, from a range of alternatives, the most suitable strengthening mortar for the historical masonry. This methodology proves to be useful to avoid the errors associated with materials that are not mechanically compatible. Special attention was devoted to fatigue and thermo-hygrometric aspects, whose effects on the masonry are often significant enough to compromise the validity of repair works.

INTRODUCTION

The recent earthquakes have shown the evident flop in the restoration works performed by means of concrete materials, that have distorted completely the original constructive characters of historical buildings. On the other hand, the new strengthening materials as epoxy resins or FRP, also establishing notable advantages in executive phases, have not shown an enough guarantee of durability yet. They emphasize a notable difference of mechanical performances compared to the historical masonry. In many instances, strengthening works are performed according to the criteria of modern technologies, modelling the buildings by means of static schemes that are not suitable for old structures [Bocca and Grazzini 2004]. The masonry buildings well upkept with effective techniques and materials characteristic of the same nature of historical factory have shown a great resistance to the seismic actions. Today the restoration knowledge has finally begun to understand the great effectiveness shown by the lighter technologies. The materials similar to that historical in terms of mechanical, chemical, thermo-hygrometric performances are to prefer [Cangi 2005]. The modern lime mortars show to be particularly compatible with the historical factory. They can to strengthen the masonry structures through reinforcement of vaults or jacketing walls.

The goal of research is to show the basic importance of the preliminary tests to qualify the most compatible product for each specific restoration work. An ad hoc experimental methodology has been developed at the Non-Destructive Test Laboratory of Politecnico di Torino to pre-qualify strengthening mortars through static, cyclic and freezing-thawing tests.

EXPERIMENTAL CAMPAIGN: INSTRUMENTATION AND MATERIALS

The materials used consisted of historical bricks and 4 different types of mortar (referred to as "A","B","C","D") produced by several firms, suitable for the following restoration techniques: application of plaster (A; C), joint closing (A; D), jacketing of masonry walls (D), reinforcement of vaults (D), consolidation by grout injection (B). Table 1 presents the mechanical characteristics of single materials investigated by test pieces 40x40x160mm shown in Figure 1.

Table 1. Mechanical characteristics of materials

Material	$E_{average}$ (N/mm^2)	$\nu_{average}$	$\sigma_{average}$ (N/mm^2)	$\Delta\%\sigma$ (6 months)
Mortar A	6208	0.12	8.27	-7.50
Mortar B	7534	0.19	10.91	+111.55
Mortar C	12678	0.23	10.34	+146.39
Mortar D	12274	0.32	24.95	+57.47
Historical brick (LT)	4099	0.08	8.09	-

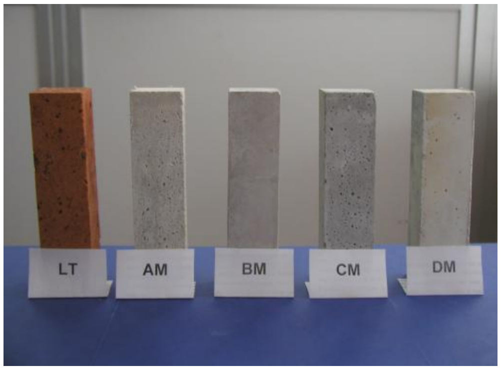


Fig. 1. Single specimens

Three different increasing scale dimension of mixed brick-mortars specimens are manufactured. First the small mixed pieces, in order to compare and to chose the most suitable mortar; then the medium and large scale dimension, continuing the study of the mortar chosen's durability. A 250 kN model 810 MTS was employed for loading tests. The freezing-thawing cycles are performed through a laboratory oven and a refrigerator cell. The methodology plans 3 progressive stages:

1. First the long-term behaviour of all 4 mortars, applied to historical brick support, are compared. Static, cyclic loading and freezing-thawing tests are carried out on the single

materials (shown in Figure 1) and on the first scale dimension mixed test pieces (shown in Figure 2), in order to study in small scale the interaction fatigue problems between strengthening mortars and historical bricks.

2. From the experimental results of point 1, a typology of mortar is chosen to continue the experimental study through an increasing dimensions of mixed brick-mortar specimens: the small walls, as shown in Figure 3. Static, cyclic loading and freezing-thawing tests are carried out by diagonal compressive test.

3. Finally, the effectiveness of the same chosen strengthening mortar is analysed by means of static compressive test on the big walls as shown in Figure 4, in order to simulate in large scale the real behaviour of the jacketing technique. A comparison is carried out with the same big specimens reinforced by injection technique.

Mixed test pieces

The Figure 2 shows the first scale dimension measuring 223x57x83mm, obtained from historical cutted bricks placed in designed timber mould and joined to 30 mm thick layer of mortar casted onto it. Each mixed test piece was labelled with “X”L, where “X” stands for the code of the relative mortar (A, B, C, D). The mixed pieces were instrumented with three pairs of transducers in order to measure the volumetric deformation: a vertical pair anchored to the plates of the MTS, another pair applied to the test piece on the opposite faces; a third pair arranged horizontally for the displacements due to detachment of materials. A pair of electrical strain gauges on the opposing vertical faces for transverse strains.

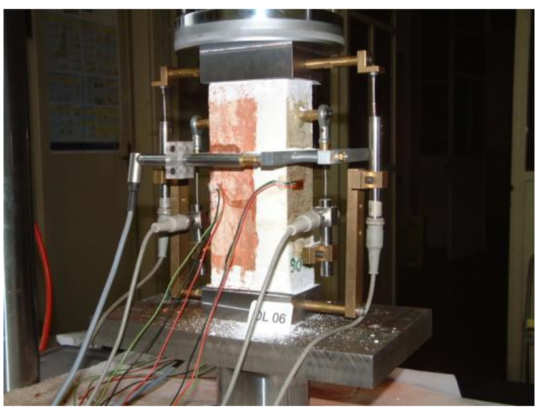


Fig. 2. Instrumentation for mixed brick-mortar test pieces

Small walls

Figure 3 shows the second scale dimension measuring 250x250x120mm. Different tests are conducted in shear loading, using the brickwork walls (4 layers of bricks) reinforced by double 20 mm thick layer of structural plaster manufactured by mortar D, chosen among the four tested for his best structural compatibility. Every specimen was equipped by a couple of displacement transducers for each side as shown in Figure 3.

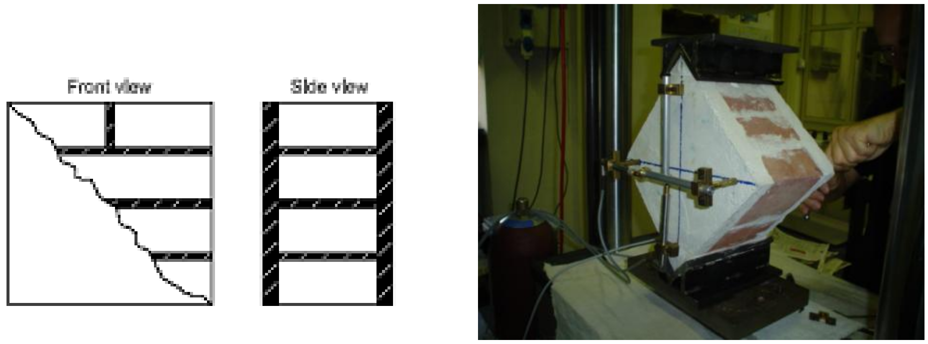


Fig. 3. Details of the reinforced specimens and shear loading test

Big walls

Finally, four masonry walls were manufactured measuring 800x800x400mm. Figure 4a shows two reference specimens (MA) reconstructing the original masonry of an historical building in Piedmont. Figure 4b shows the other two specimens reinforced by jacketing technique (RMA). The pieces were instrumented with three pairs of transducers, as shown in Figure 5.

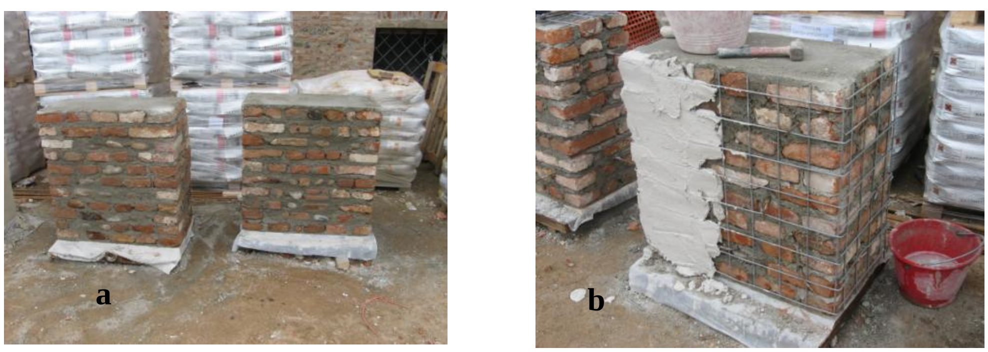


Fig. 4. a) Two specimens reference of the historical masonry (MA) – b) Specimens reinforced through jacketing with still mesh Φ5mm/10x10cm (RMA)

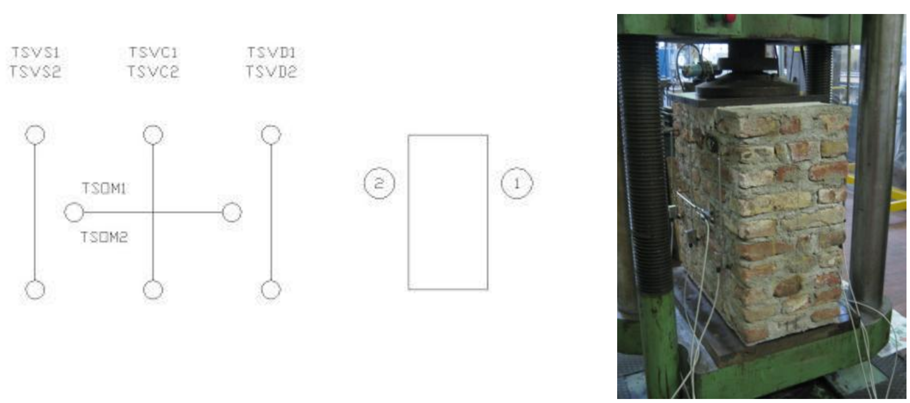


Fig. 5. Position of transducers

RESULTS OF EXPERIMENTAL CAMPAIGN: FIRST STAGE

Single materials

For mortar B and D, the evolution of mechanical characteristics in the time due to the maturation effects has been analysed. The results are described in Table 2 and in Figure 6. A considerable increase in the compressive strength is registered between 28 and 90 days.

Table 2. Mechanical characteristics during maturation: mortar B and D

	Mortar B				Mortar D			
Days	$\sigma_{average}$ (N/mm^2)	$\Delta\sigma$ % (28-d)	$E_{average}$ (N/mm^2)	ΔE % (28-d)	$\sigma_{average}$ (N/mm^2)	$\Delta\sigma$ % (28-d)	$E_{average}$ (N/mm^2)	ΔE % (28-d)
28	12.08	-	7389	-	20.64	-	10691	-
90	19.60	+64.71	10685	+44.62	28.25	+36.87	12436	+16.32
150	19.16	+58.61	8439	+14.21	28.52	+38.18	12150	+13.64
210	18.14	+50.16	10634	+43.92	29.24	+41.70	14468	+35.32

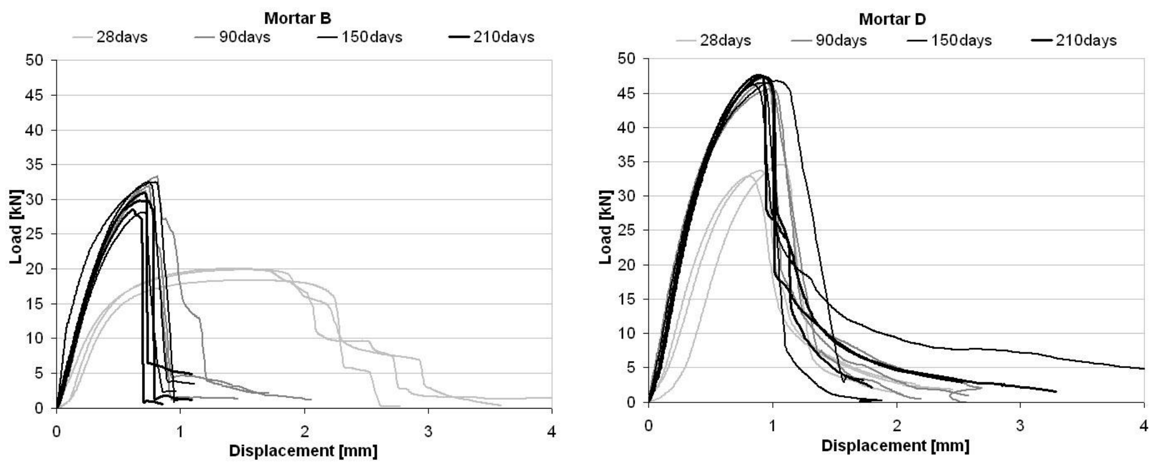


Fig. 6. Compression test during maturation: mortar B and D

The test piece of mortar B and D were subjected also to freezing-thawing tests. None of the specimens B remained intact after 25 cycles (from 20°C to –10°C). On the contrary mortar D showed a significant increase in resistance (+34.27%). After 50 cycles there is a decrease in compressive strength, bringing the average values close to the virgin reference.

Mixed test pieces

Table 3 shows the results of the compression tests performed in order to determine the failure load. Others mixed test pieces were subjected to 28 freezing-thawing cycles. In Table 4 it's possible to observe the medium and great increase in strength for CL and DL series.

Table 3. Results of preliminary static tests on mixed test pieces

Series	Test piece	P_{max} (KN)	σ_{max} (N/mm^2)	$\sigma_{average}$ (N/mm^2)	E (N/mm^2)
AL	AL02	102.75	19.30	15.40	11988
	AL04	59.76	11.49		14157
BL	BL01	108.51	22.17	16.89	16940
	BL02	52.30	11.60		4400
CL	CL01	40.78	9.71	12.58	6597
	CL02	76.98	15.46		12478
DL	DL01	58.50	12.10	12.04	6191
	DL02	60.45	11.98		8106

Table 4. Results of static tests after freezing-thawing cycles

Series	Test piece	Condition	P_{max} (KN)	σ_{max} (N/mm^2)	$\sigma_{average}$ (N/mm^2)	$\Delta\sigma$ %	E (N/mm^2)
AL	AL03	cracked	95.54	19.78	15.88	+3.15	10050
	AL06	detached	81.00	15.83			8151
	AL08	detached	59.30	12.03			6701
BL	BL07	cracked	76.30	14.23	13.88	-17.81	6250
	BL10	cracked	66.50	13.52			6582
CL	CL06	whole	104.50	19.92	15.52	+18.25	10604
	CL08	whole	54.62	11.13			7191
DL	DL08	whole	107.40	21.52	22.87	+89.93	35358
	DL07	whole	129.30	24.22			16249

Cyclic tests were the most significant stage. The high value selected for the cyclic load (70% of the static load) was designed to make the test severe enough despite the short duration (100000 cycles – 1.3 Hz). The evolution of the volumetric deformation was analysed, since its propensity to assume negative values (increase in volume) can reflect a lesser degree of collaboration between the two materials, or even their detachment at the interface. Together with the vertical and horizontal deformations, this is an indicator of the validity of the combination between the historical material and the strengthening mortar. The test was performed through four steps:

- initial 70% loading-unloading test (3 cycles);
- 70% cyclic test (100000 cycles);
- final 70% loading-unloading test (1 cycle);
- post-cyclic compression test to failure.

In Figure 7 in a typical σ-ε curve of a cyclic fatigue test it is possible to identify three distinct stages: stage I, where deformations are seen to increase rapidly (accounting for ca 10% of the service life of the test piece); stage II, of stabilisation, where the deformations increase gradually at a virtually constant stress (10-80% of test piece life); stage III, with a rapid increase till failure. Various authors [Minh-tan et al. 1993, Mu et al. 2005] have shown that the fatigue life of a material subjected to cyclic loading tests is strictly correlated to the evolution of the deformations during stage II.

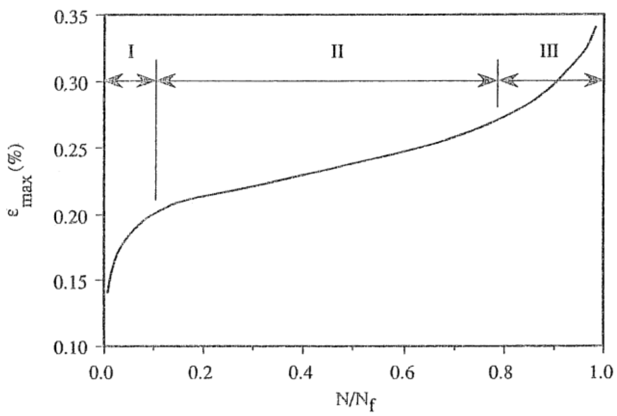


Fig. 7. Monoaxial cycles compression test σ-ε curve

By analogy with the method suggested for concrete [Taliercio and Gobbi 1996], the evolution of vertical deformations over time is analysed as the primary parameter for predicting the fatigue strength [Carpinteri et al. 2006]. The goal is to ascertain whether the fatigue life of the mixed brick-mortar system also depends on the rate of increase of vertical deformations during stage II (*secondary creep rate*). In figure 8 it can be seen that the test pieces that reached failure displayed a steeper slant in the stage II section of the curve, followed, at ca 80-90% of test piece life, by a sudden increase at stage III (failure). Conversely, the curves obtained for the pieces that passed the100000 cycles mark displayed a lesser slant, still far from the failure. From the results of the cyclic tests described above, through linear interpolation between 20% and 80% of secondary creep values, derivatives $\partial\varepsilon_v / \partial n$ (i.e., the variations in the deformation vs. time curve during stage II) were worked out. Through a linear regression on the logarithmic scale [Grazzini 2004, 2006], it is possible to plot the data in a diagram to obtain an analytical relationship (1) between secondary creep variations, $\partial\varepsilon_v / \partial n$, and the number of cycles (N) to fatigue failure:

$$N = 1839.92 \cdot \left(\frac{\partial \varepsilon_v}{\partial n} \right)^{-0.7284} \qquad (1)$$

A valid correlation was established between secondary creep rate ($\partial\varepsilon_v/\partial n$) during stage II and fatigue life (number of cycles to failure, N). By performing a certain number of cycles on the material until it reaches the stage where deformations increase at a constant rate, it's possible to predict fatigue life. Failure occurs when a deformation limit (correlated to the loading level) is reached, after which the volume begins to increase; if the deformation rate is too slow, the material does not reach the limit and the volumetric deformation remain positive. In some samples, the theoretical value N_{the} was found to be lower than the value obtained from laboratory tests. From a case-by-case analysis it can be seen that relationship (1), which is a function of the secondary creep rate, is able to indicate the onset of the crisis of the brick-mortar systems immediately preceding the final value of the testing cycles. The theoretical value obtained from expression (1), that was smaller than the actual value, corresponded to the time when a significant variation in trend was recorded. The numerical analysis proved very sensitive to the initial signs of weakening in the brick-mortar system [Grazzini 2006].

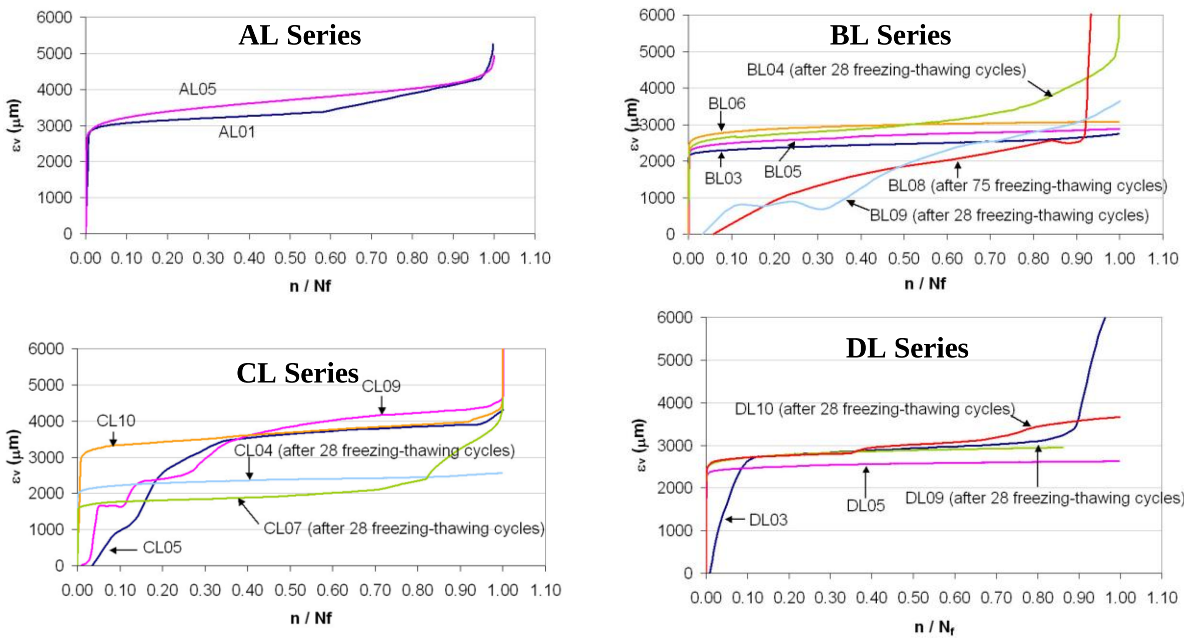


Fig. 8. Series cyclic tests: max vertical deformation

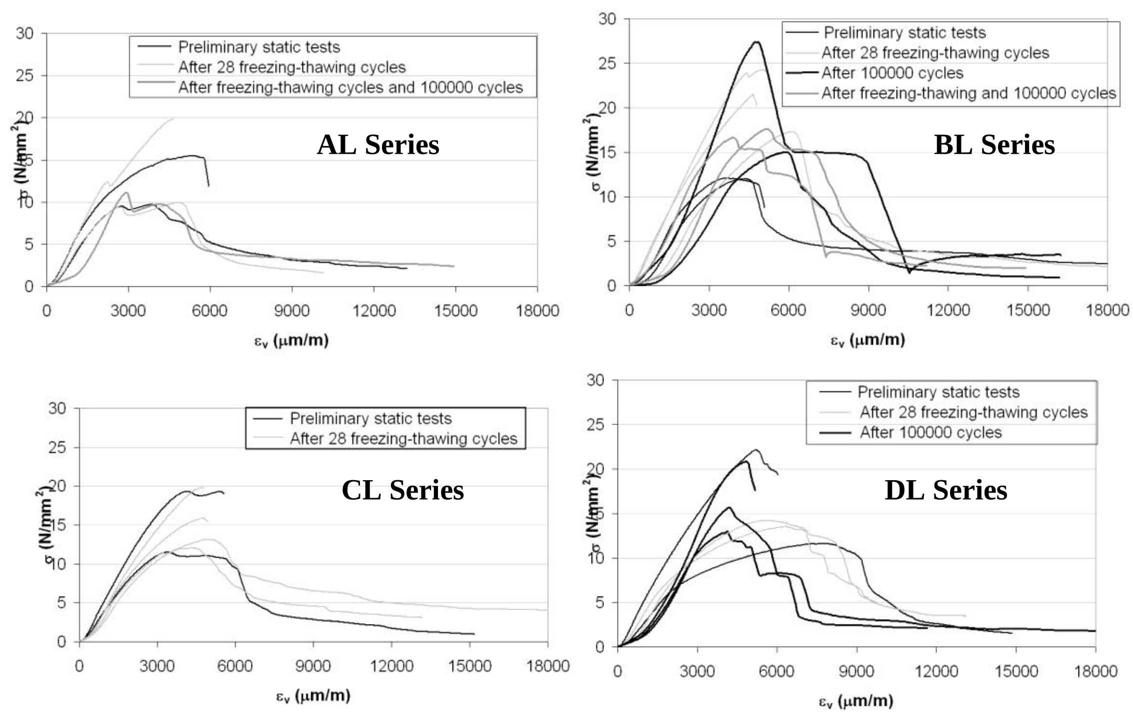
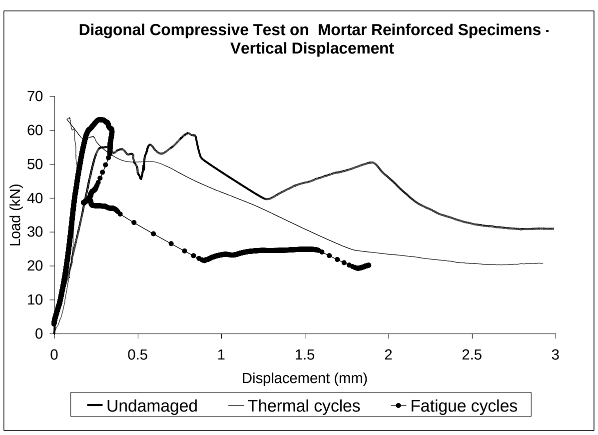


Fig. 9. Series static tests

The figure 9 shows the static tests. The values remained within the average of the two preliminary tests, save for the series DL, which displayed a considerable increase in strength. The static curves after freezing-thawing test revealed a more brittle behaviour. BL test pieces, instead, retained a good degree of ductility. The BL and DL test pieces series that passed 100000 cycles mark were tested on to failure. The DL series displayed a noticeable increase in their mechanical properties and brittleness (+138%). Some CL and DL test pieces were subjected both to freezing-thawing test and to cycling loading. Piece CL maintained a static behaviour similar to the weakest preliminary test result and a decrease of brittleness (-75.8%). In the DL series, instead, an appreciable increase in strength was mated to a lesser degree of brittleness compared to the test pieces subjected to cyclic loading only.

RESULTS OF EXPERIMENTAL CAMPAIGN: SECOND STAGE

The results of the diagonal compressive test are reported in Figure 10a after thermal and fatigue damage and in undamaged condition. Environmental actions were simulated through freezing-thawing cycles from 60°C to -15°C, 8 thermal cycles, each during 25 hours. Long-term behaviour was analysed through a fatigue cyclic loading test: 100000 cycles at 1 Hz, 50% of the static load. After these damage tests the shear test was followed through a diagonal compressive test. It can be observed that the maximum shear resistance for three reinforced brickwork was substantially unchanged. The mechanical behaviour was different between reinforced brickworks: ductile collapse for specimen subjected to the thermal cycles, brittle collapse for specimen subjected to the fatigue cycles. Failure mechanism was the same for these MR specimens, with a diagonal cracking in loading direction [Bocca et al. 2008].



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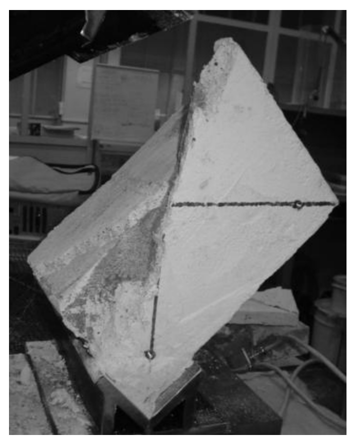

b

Fig. 10. a) Diagonal compressive test on MR specimens after thermal and fatigue damage and in undamaged condition – b) MM02 specimen after collapse.

RESULTS OF EXPERIMENTAL CAMPAIGN: THIRD STAGE

The big walls specimens were submitted to static tests, in order to verify the effectiveness of the mortar D to guarantee an increase of strength and to limit the stiffness of masonry structure. Table 5 and Figure 11 show the results. It were manufactured also two other big walls reinforced by injections of lime mortar (IMA), in order to compare the jacketing and injections technique. The masonry specimens without reinforcement (MA) have substantially shown a similar behaviour and a good ductility post-failure. The walls specimens reinforced by injections of lime mortar (IMA) have shown a small decrement of the compression strength (-3.44%) and a strong decrement of the elastic modulus (-37.95%) in comparison to the virgin champions (MA). This shows that the injections technique used in this masonry structure has not produced any benefit. The good result of this technique not only depends on the choice of the most compatible mortar, but also on the dimensions of masonry inside voids.

Table 5. Results of static compressive tests

Specimen	Typology	P_{max} (KN)	$P_{average}$ (KN)	E (N/mm^2)	$E_{average}$ (N/mm^2)	K (N/mm)	$K_{average}$ (N/mm)
MA 01	Historical masonry	600.69	**532.37**	7062	**7147**	1126705	**1117404**
MA 02	Historical masonry	464.04		7231		1108102	
IMA 01	Injected masonry	515.95	**514.05**	4913	**4435**	1287808	**1283092**
IMA 02	Injected masonry	512.14	***-3.44%***	3956	***-37.95%***	1278376	***+14.83%***
RMA 01	jacketing walls	769.75	**869.04**	5931	**6940**	1099971	**1306238**
RMA 02	jacketing walls	968.33	***+63.24%***	7948	***-2.90%***	1512505	***+16.90%***

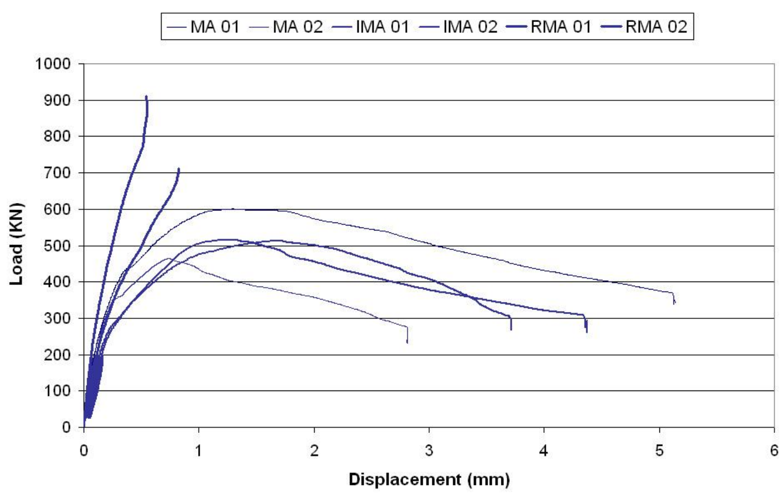

Fig. 11. Load-displacement curve

In a masonry structure reinforced by jacketing technique the loads will be distributed in proportion to the stiffness of the two materials (masonry and strengthening mortar). It needs therefore to pay attention to the use of too strong strengthening materials, because a notable difference of stiffness compared to the historical masonry structure would promote dangerous tensions to the interface and the separation of the reinforced layer. It can jeopardize a homogeneous answer of the masonry building in presence of seismic actions. The masonry walls reinforced by jacketing (RMA) have shown a considerable increase of strength (+63.24%), without nevertheless to alter the global behaviour of the structure.

CONCLUSIONS

An ad hoc experimental methodology has been developed to pre-qualify, as a preliminary design stage for restoration works, the most compatible strengthening mortar applied to historical masonry structures. The evolution in the time of the mechanical characteristics, due to maturation, thermo-hygrometric and fatigue loading condition has been investigated through static, cyclic loading and freezing-thawing tests on different reinforced masonry specimens. The experimental methodology is useful to identify a number of key parameters for interpreting the long-term behaviour of historical brick-strengthening mortar system.

The analytical formula based on secondary creep variations during stage II demonstrated a great sensitivity, by supplying the number of cycles after which the collaboration between the two materials begins to be undermined, without necessarily resulting in test piece failure.

The tests carried out through mixed specimens of medium and big dimensions scale have allowed to better analysis the short and long-term effectiveness of a specific strengthening mortar applied to a specific historical masonry structure reconstructed in the laboratory.

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