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# Fatigue behaviour analysis for the durability prequalification of strengthening mortars

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**Abstract.** An innovative laboratory procedure used as a preliminary design stage for the pre-qualification of strengthening mortars applied to historical masonry buildings is described. In the analysis of the behaviour of masonry structures and their constituent materials, increasing importance has been assumed by the study of the long-term evolution of deformation and mechanical characteristics, which may be affected by both loading and environmental conditions. Through static and fatigue tests on mixed specimens historical brick-reinforced mortar it has been possible to investigate the durability of strengthening materials, in order to select, from a range of alternatives, the most suitable for the historical masonry. Cyclic fatigue stress has been applied to accelerate the static creep and to forecast the corresponding creep behaviour of the historical brick-strengthening mortar system under static long-time loading. This methodology has proved useful in avoiding the errors associated with materials that are not mechanically compatible and guarantees the durability of strengthening work. The experimental procedure has been used effectively in the biggest restoration building site in Europe, the Royal Palace of Venaria, and it is in progress of carrying out at the Special Natural Reserve of the Sacro Monte di Varallo, in Piedmont (Italy).

## 1. Introduction

The restoration of historical masonry buildings is a complex process, when the compatibility of strengthening materials plays a fundamental role for the durability of reinforced structures. Historical buildings often require drastic interventions, performed with techniques that make extensive use of the new products. The tests conducted are often limited to determining their ultimate strength, disregarding their durability and their interaction with pre-existing materials. Unfortunately, where technical, conceptual and cultural aspects are concerned, there is not much clarity yet about the use of modern materials in ancient constructions. Recent earthquakes have shown the clear failure of restoration work performed with the use of concrete materials, whose excessive stiffness has completely distorted the original characteristics of historical masonry buildings. In many instances, restoration works are performed according to the criteria of modern technologies, with newly-developed materials, modelling the buildings according to resisting schemes that are not appropriate to structures created in stages at different times, thereby giving rise to hybrid forms of behaviour that cannot be readily foreseen [1].

For years the Non Destructive Testing Laboratory of the Department of Structural and Geotechnical Engineering of the Politecnico di Torino has been working on a line of research within the framework of an important convention stipulated with the Cultural Heritage Division of the

Piedmont Region. The field of application is the Royal Palace of Venaria Reale that represents the most significant restoration project under way in Europe (figure 1). The theme is the “Study of the quality of the applications of innovative materials in strengthening interventions on historical artefacts”. Recently the research has been carried out also at the Special Natural Reserve of the Sacro Monte di Varallo in Piedmont (UNESCO heritage site), financed by Piedmont Region through RE-FRESCOS project.

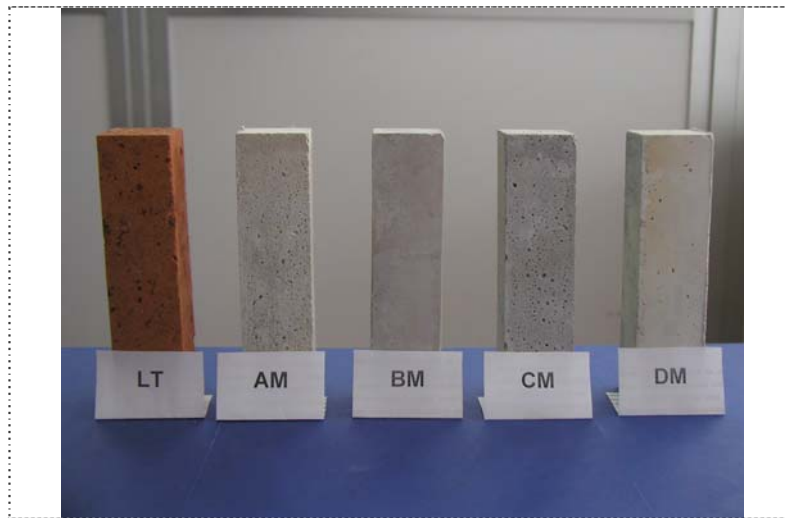
The goal of the research is the experimental study of the long-term behaviour of the constituent materials of the masonry, with special regard to the mechanical interaction between historical bricks and modern strengthening mortars. Their long-term behaviour remains unknown in several respects, especially when they are applied to deteriorated historical masonry structures, whose mechanical behaviour is often difficult to analyse and has to be assessed case by case. Through a rather fast laboratory procedure, this method supplies useful indication for selecting, from a range of alternatives, the product that is best in keeping with the mechanical characteristics of the historical material, thereby avoiding the errors associated with materials that are not mechanically compatible [2]. By focusing on the evolution of the deformation parameters in accordance with recent damage models, it is possible to compare the characteristics of the materials, assess their interaction and fatigue behaviour. An important part was devoted to the execution of cyclic tests, leading to a more comprehensive understanding of the fatigue phenomena that jeopardise the brick-mortar system. Special attention was devoted to thermo-hygrometric aspects, which are often overlooked, but whose effects on the masonry system are often significant enough to compromise the validity of strengthening interventions.



**Figure 1.** Royal Palace of Venaria Reale

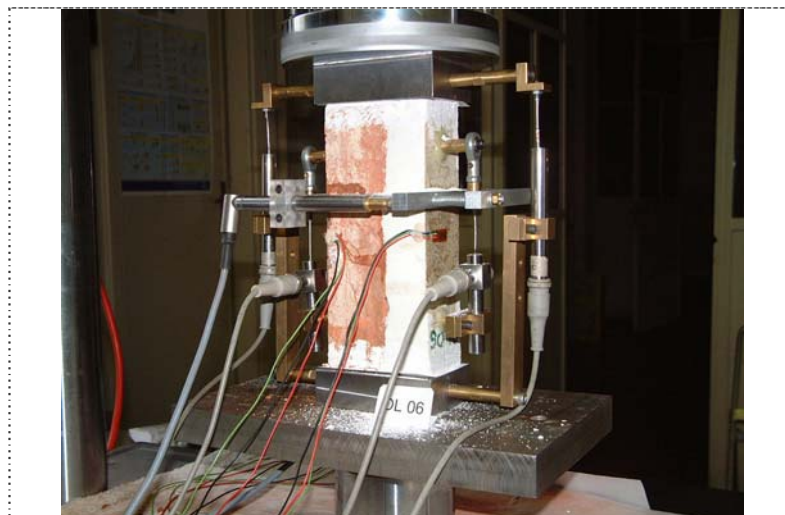
## **2. Experimental campaign: instrumentation and materials**

The materials are bricks, from the Royal Palace of Venaria Reale, and 4 different types of mortars produced by several firms (codified as “A”, “B”, “C”, “D”), suitable for the following restoration techniques: reinforcement by structural plaster (A; C), joint closing (A; D), jacketing of masonry walls or reinforcement of vaults (D), consolidation by grout injection (B). The mechanical characteristics were investigated by means of 6 test pieces 40x40x160mm for each single material (figure 2), subjected to static tests. Each mortar test piece was labelled with “XM” where “X” stands for the code of the relative mortar (A, B, C, D); the brick test piece was labelled with “LT”.



**Figure 2.** Single specimens

Special attention was devoted to the study of ad hoc mixed brick-mortar test pieces, in order to study in small scale the interaction fatigue problems between strengthening mortar and historical brick. These test pieces were subjected both to static and to cyclic loading tests and to freezing-thawing tests, in order to analyse the variations in the deformation status of the materials under the various loads that can affect the masonry structure after the restoration process. The material used to produce the mixed tests pieces (figure 3) was obtained from historical bricks cutted, using specially designed timber mould measuring 223x57x83mm (30mm thick layer of mortar). The brick surface, on which the product was applied, was roughened through chipping with a scalpel, brushing with a steel brush, and making two 10 mm diameter holes with drilled to a depth of 10 mm. The treatments simulate roughness and irregularity of the masonry surface that in real executive phases can improve the adhesion of strengthening plaster.



**Figure 3.** Instrumentation for mixed brick-mortar test pieces

Each mixed piece was labelled with “X”L, where “X” stands for the code of the relative mortar. Cyclic and static compressive tests were performed with the aid of a 250 KN model 810 MTS. The mixed pieces were instrumented with three pairs of transducers, according to the scheme shown in

figure 3: a vertical pair was anchored to the plates of the MTS and another vertical pair was applied directly to the test piece on the opposite faces of the two materials; finally, a third pair arranged horizontally was used for measuring the displacements due to bulging. Completing the system, a pair of electrical strain gauges on the opposing vertical faces of the test pieces measured transverse strains. In this manner it's possible to measure all the axial deformations (in vertical, horizontal and transverse directions), whose algebraic sum yields the volumetric deformation [3].

### 3. Results of the experimental campaign

Table 1 shows the results of static tests on single materials pieces measuring 40x40x160mm.

**Table 1.** Elastic modulus and compression results of individual materials

Material	$E_{\text{average}} \text{ (N/mm}^2\text{)}$	$\nu_{\text{average}}$	$\sigma_{\text{average 28days}} \text{ (N/mm}^2\text{)}$	$\Delta\% \sigma \text{ 6 months}$
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	-

**Table 2.** Results of preliminary static tests on mixed test pieces

Series	Test piece	$P_{\text{max}} \text{ (KN)}$	$\sigma_{\text{max}} \text{ (N/mm}^2\text{)}$	$\sigma_{\text{average}} \text{ (N/mm}^2\text{)}$	$E \text{ (N/mm}^2\text{)}$
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 3.** Results of static tests after freezing-thawing cycles on mixed test pieces

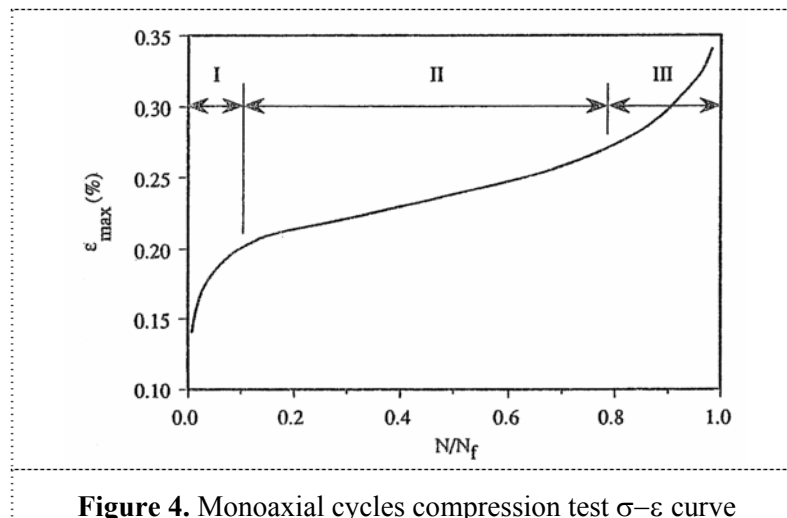
Series	Test piece	Condition	$P_{\text{max}} \text{ (KN)}$	$\sigma_{\text{max}} \text{ (N/mm}^2\text{)}$	$\sigma_{\text{average}} \text{ (N/mm}^2\text{)}$	$\Delta\sigma \%$	$E \text{ (N/mm}^2\text{)}$
AL	AL03	cracked	95,54	19,78	15,88	+3,15	10050
	AL06	detached	81,00	15,83			8151
	AL08	detached	59,30	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

The cyclic loadings on mixed test pieces were the most significant part of the testing campaign. Before cyclic fatigue loading, static tests were performed in order to determine the failure load (table 2). Other mixed test pieces were subjected to 28 freezing-thawing cycles. Of special interest is a great increase of strength observed after freezing-thawing cycles (table 3).

The high value selected for cyclic load (70% of static load) was designed to make the test severe enough despite the short duration in the time (100000 cycles – 1.3 Hz), and to highlight the potential of several indicators monitored over time. The evolution of the volumetric deformation of mixed pieces was analysed. Its propensity to negative values (increase in volume) can reflect a lesser degree of collaboration between the two materials, or even their detachment at the interface. 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 a typical  $\sigma$ - $\varepsilon$  curve of a cyclic fatigue test (figure 4) 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 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 [4]. Various authors [5-6] have shown that fatigue life of a material subjected to cyclic loading tests is strictly correlated to the evolution of the deformations during stage II.



**Figure 4.** Monoaxial cycles compression test  $\sigma$ - $\varepsilon$  curve

By analogy with the method suggested for concrete [7], the evolution of vertical deformations over time was analysed for predicting and quantifying fatigue strength of material [3]. The goal is to ascertain whether 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 figures 5-8 it can be seen that the test pieces which reached failure (before 100000 cycles, see table 4) 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 from pieces that passed 100000 cycles mark displayed a lesser slant, which remained virtually the same, reflecting an effective behaviour still far from failure.

From the results of cyclic tests described above, through linear interpolation between 20% and 80% of secondary creep values (figure 9), 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 logarithmic scale [3], it is possible to plot the data in a diagram in order to obtain an analytical relationship (1) between secondary creep variations,  $\partial\varepsilon_v / \partial n$ , and the number of cycles (N) to fatigue failure:

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

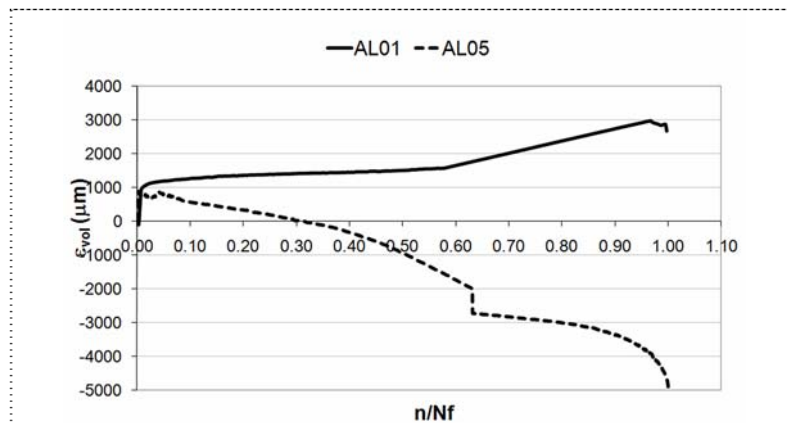


Figure 5. AL series cyclic tests: max vertical deformation

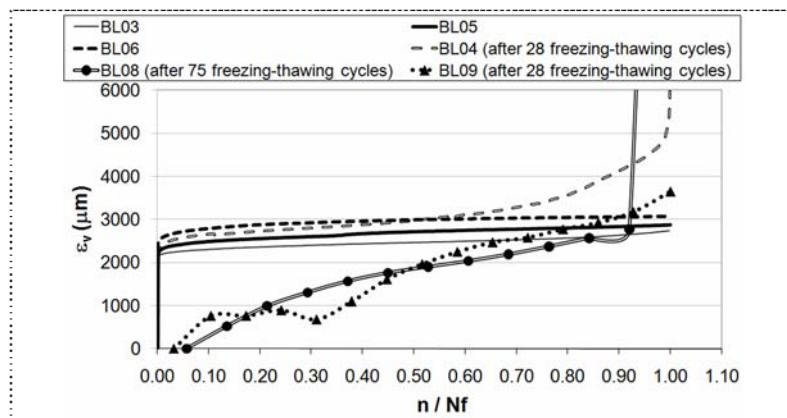


Figure 6. BL series cyclic tests: max vertical deformation

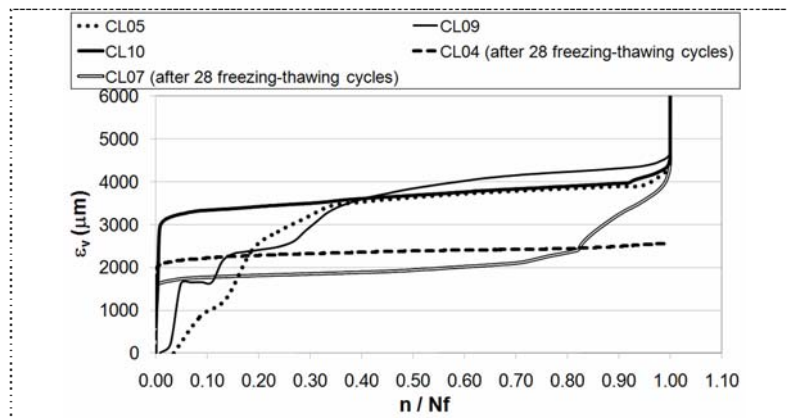
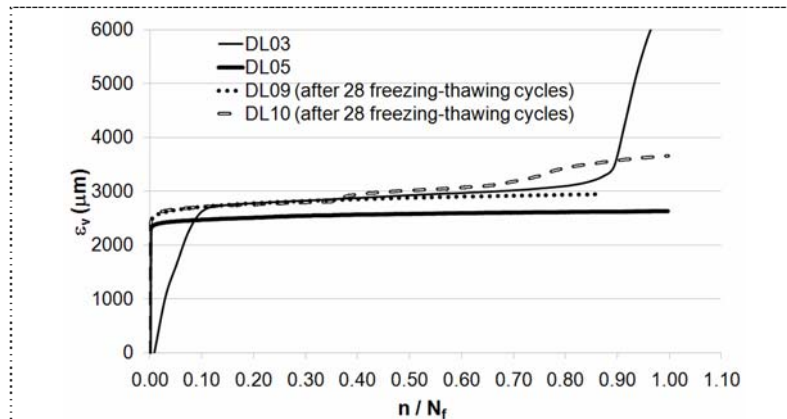
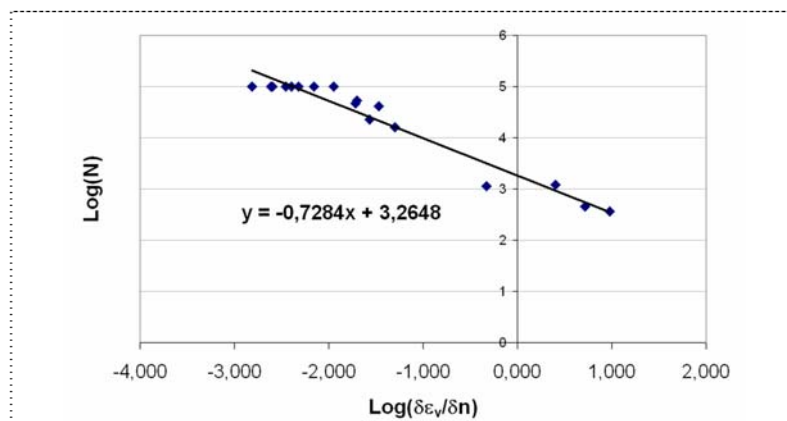


Figure 7. CL series cyclic tests: max vertical deformation





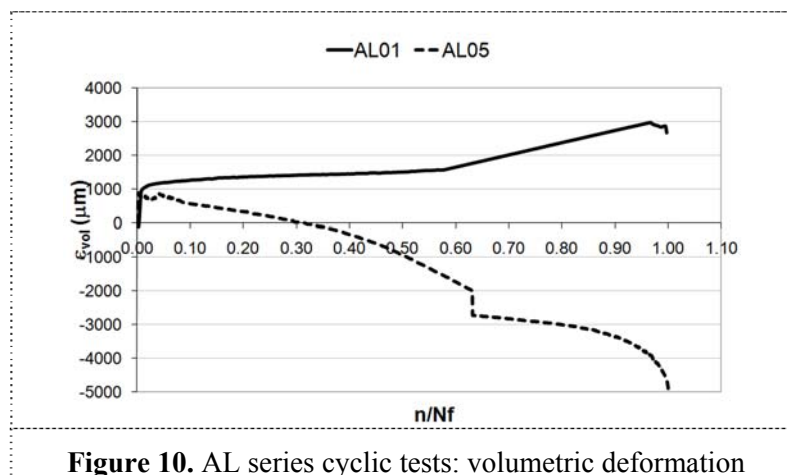
**Figure 8.** DL series cyclic tests: max vertical deformation



**Figure 9.** Fatigue life of mixed test pieces  $\partial\varepsilon_v / \partial n$  chart

**Table 4.** Analysis of the data

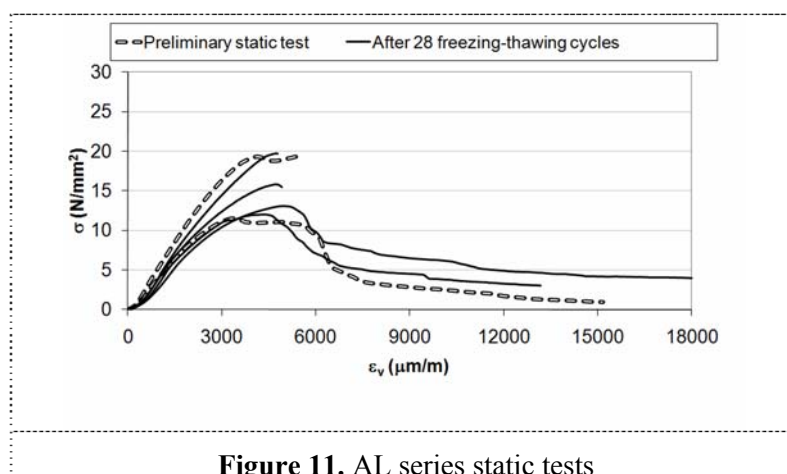
<i>Test piece</i>	<b>n</b>	$\partial\varepsilon_v/\partial n$	<b>LogN</b>	<b>Log(<math>\partial\varepsilon_v/\partial n</math>)</b>	<b>N<sub>the</sub></b>
AL01	22380	0,0270	4,350	-1,569	25583
AL05	53465	0,0198	4,728	-1,703	32029
BL03	100000	0,0047	5,000	-2,323	90605
BL05	100000	0,0040	5,000	-2,398	102716
BL06	100000	0,0024	5,000	-2,612	147056
CL05	461	5,1818	2,664	0,714	555
CL09	1223	2,5110	3,087	0,400	941
CL10	15835	0,0501	4,200	-1,300	16294
DL03	1149	0,4704	3,060	-0,328	3187
DL05	100000	0,0015	5,000	-2,813	206028
DL06	100000	0,0070	5,000	-2,155	68328
BL04	40993	0,0340	4,613	-1,469	21612
BL09	360	9,4729	2,556	0,976	358
CL04	100000	0,0035	5,000	-2,454	112832
CL07	46622	0,0192	4,669	-1,717	32795
DL09	100000	0,0025	5,000	-2,594	142671
DL10	100000	0,0113	5,000	-1,947	48171



**Figure 10.** AL series cyclic tests: volumetric deformation

The goal is to focus on the deformation response of material subjected to fatigue tests. 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 deformations increase at a constant rate, it is possible to predict fatigue life with a good degree of approximation. 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, material does not reach limit value during cyclic loading and the values of volumetric deformation remain positive.

In some samples, the theoretical value of cycles to failure  $N_{the}$  was found to be lower than that obtained from laboratory tests (table 4). The relationship (1) was able to indicate the onset of crisis in the brick-mortar systems immediately preceding the final value of testing cycles. The analysis of horizontal and volumetric deformations, in fact, demonstrated that the theoretical value obtained from expression (1) corresponded to the time when a significant variation in trend was recorded. I. e. for piece AL05 in figure 10 volumetric deformations shifted to negative sign (propensity to bulge due to poor vertical collaboration or detachment at the interface between the two materials). The methodology and the numerical analysis proved very sensitive to the initial signs of weakening in the brick-mortar system, indicating clearly the onset of a crisis due to fatigue [3].



**Figure 11.** AL series static tests

Figures 11-14 illustrate the static tests performed on mixed test pieces. The values obtained for a majority of the series remained within the average of the two preliminary tests, save for the series DL, which displayed a considerable increase in strength. In most cases, static curves after freezing-thawing revealed a more brittle behaviour. Test pieces of BL and DL series that passed 100000 cycles mark

were tested to failure: the DL series displayed a noticeable increase of their mechanical properties. Some CL and DL test pieces were subjected both to freezing-thawing test and to cycling loading: CL maintained a static behaviour similar to the weakest preliminary test result; instead in the DL series an appreciable increase of strength was mated to a lesser degree of brittleness compared to the test pieces subjected to cyclic loading only.

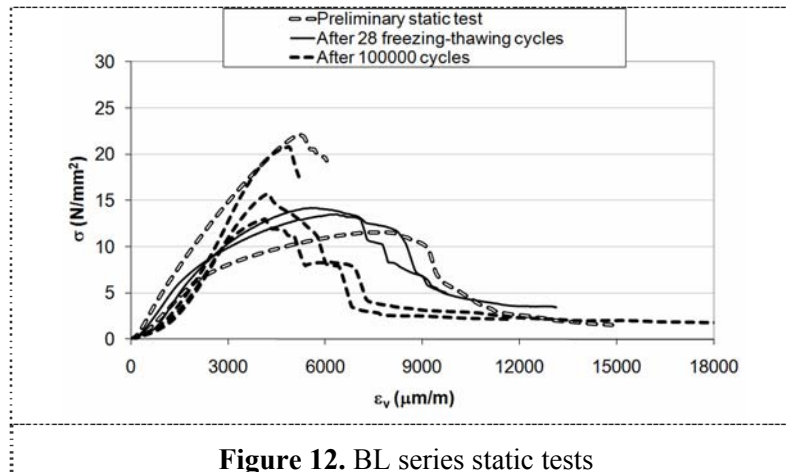


Figure 12. BL series static tests

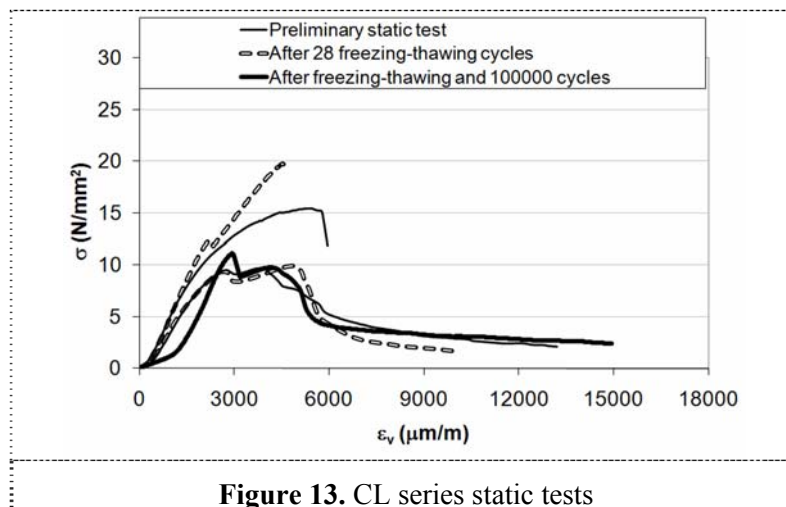


Figure 13. CL series static tests

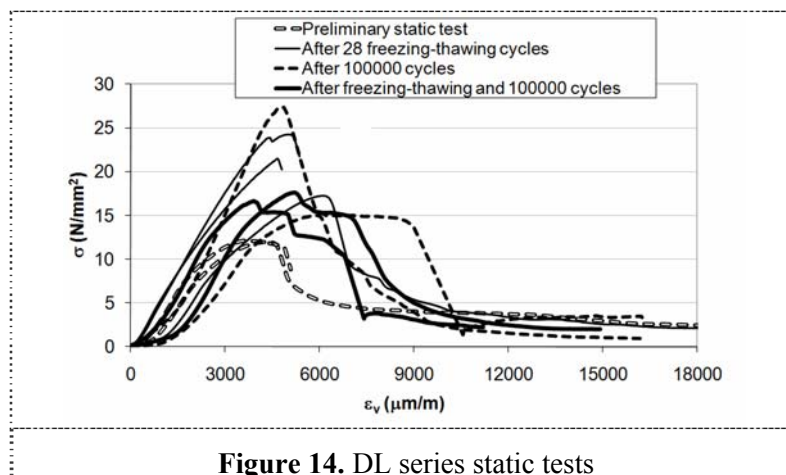


Figure 14. DL series static tests

#### 4. Conclusions

Despite the widespread use and great variety of strengthening products currently available on the market, to this day there is no valid reference to standardised testing procedures supplying effective evaluation criteria for the long-term behaviour of these products. The use of more similar materials to the mechanical characteristics of the historical masonries represents the most appropriate choice for a consolidation intervention able to guarantee the durability.

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 mixed test 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 constant monitoring of horizontal and volumetric deformations during the cyclic tests conducted on mixed test pieces represented the main innovation in the proposed method. Their evolution proved very sensitive to the initial signs of crisis in the collaboration between the two materials, thereby facilitating the interpretation of collapse mechanisms. In accordance with the theories formulated by different authors, the simple analytical formula based on secondary creep variations during stage II demonstrated the same sensitivity and the same degree of accuracy as the volumetric deformation, 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. By performing a certain number of cycles on the material, until it reaches the stage when the deformations grow at a constant rate, it therefore becomes possible to predict the fatigue life of the brick-mortar combination with a good degree of approximation, without having to perform long series of fatigue cycles. The severity of freezing-thawing tests helped to achieve a more comprehensive assessment of the long-term behaviour of the materials, confirming the influence of this type of thermo-hygrometric stresses on the masonry system.

Based on the results obtained from the tests, it can be stated that mortar D displayed a satisfactory behaviour when applied to the historical masonry of the Royal Palace of Venaria Reale.

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