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Durability evaluation of reinforced masonry by fatigue tests and acoustic emission technique

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SUMMARY

An experimental analysis has been carried out on the long-term behaviour of composite specimens and walls made with historical brickwork. The test pieces were subjected both to static and to cyclic loading tests (accelerate static creep) and to freezing-thawing thermo-hygrometric tests in order to study the durability of different strengthening mortars.

The acoustic emission (AE) monitoring technique was also used to assess the damage localization and to predict the time to failure of the strengthened walls during fatigue tests. The AE is a very effective non-destructive technique that permits to estimate the amount of energy released during fracture propagation.

Damage evolution during fatigue compressive loading, in terms of measured strains and the AE counting number, can be divided into three stages; fatigue life can be predicted from the slope of the AE counting number rate diagram. Starting from an AE monitoring, a special methodology has been developed to predict the service life of creep damaged masonry structures.

The novelty of this work consists in the experimental confirmation that the AE technique is able to analyse the creep curves of masonry strengthening mortars. Therefore, it demonstrated that by the AE technique, it is also possible to evaluate the durability of strengthening materials subjected to load histories in the time. Copyright © 2013 John Wiley & Sons, Ltd.

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KEY WORDS: strengthening mortar; masonry; acoustic emission; damage; creep behaviour; cyclic loading

1. INTRODUCTION AND RESEARCH AIM

The restoration of historical buildings is a complex process, in that newly developed strengthening materials, whose long-term effects have not yet been fully tested, may interact adversely with the materials making up the masonry. The tests conducted are often limited to determining their ultimate strength, disregarding their durability and their compatibility with pre-existing materials.

In the last years, the Non-Destructive Testing Laboratory in the Department of Structural and Geotechnical Engineering of the Politecnico di Torino conducted several researches on the applications of innovative materials in historical building strengthening works. The field of application is the restoration site of the Royal Palace of Venaria Reale, one of the largest Savoy mansions near Turin and, at present, the biggest restoration site in Europe in terms of size and complexity [1,2]. The goal of this research project is to develop an experimental methodology for the preliminary selection of strengthening materials and the evaluation of their long-term compatibility with historical masonry. This methodology has proved useful in avoiding the errors associated with materials that are not mechanically compatible and guarantees the durability of strengthening work.

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On the basis of a detailed study of the main strengthening techniques and the durability problems encountered in recent years in the restoration works of the Italian historical heritage, it proved possible to define an experimental campaign, including the different types of loads and actions [3,4] in order to study the fatigue phenomena on the brick–mortar system. Special attention was devoted to fatigue and thermo-hygrometric aspects, which are often overlooked, but whose effects on the masonry system are significant enough to compromise the validity of repair work.

One of the most common method used to reinforce masonry structures is to provide single-sided or double-sided of structural mortar layers (Figure 1), increasing the material strength and ductility [3,4].

The laboratory tests were carried out on four strengthening mortars, which were chosen among the most important on the market. After a first selection phase among the four products in which their mechanical characteristics were compared with those of historical bricks, the most compatible strengthening mortar has been selected. Later, the study of his long-term behaviour has been carried on with medium-scale dimension specimens in order to better simulate in laboratory the durability of strengthened masonry wall.

In particular, two progressive experimental stages were performed:

1. The first one on single specimens made by four different mortars, plus one by historical brick and later on composite specimens produced by brickwork samples interfaced with four different strengthening mortars.
2. The second one on brickwork walls reinforced by only one structural mortar chosen from those previously tested.

The laboratory tests were carried out in order to assess the fatigue strength and the structural compatibility between the different materials. Moreover, in order to analyse the masonry element damage evolution during the tests and to obtain information on the criticality of the ongoing process, the acoustic emission (AE) technique was used on reinforced brickwork walls.

The AE technique is a very effective non-destructive methodology useful to identify defects and damage in masonry structures [5–7]. In particular, a signal-based procedure is proposed to evaluate the damage evolution and the decay of structural mechanical parameters. It consists in analysing the AE signals to evaluate the damage evolution and to localise crack sources [8,9].

2. EXPERIMENTAL CAMPAIGN: INSTRUMENTATION AND MATERIALS

2.1. Single and mixed test pieces

The materials consist of historical bricks from the Royal Palace of Venaria Reale and four different mortars referred to as ‘A’, ‘B’, ‘C’ and ‘D’. They are produced by different manufacturers and are

Figure 1. Application of mortar for jacketing wall inside the Royal Palace of Venaria Reale.

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suitable for the consolidation of monumental masonry structures by single-sided or double-sided of structural mortar layers. The mechanical characteristics of the materials have been investigated by means of three test pieces $40 \times 40 \times 160\,mm^3$ for each strengthening mortar.

This experimental research, further to analyse the mechanical characteristics of single materials, also has devoted special attention to the study of composite brick–mortar specimens in order to better analyse the mechanical interaction between the materials under fatigue tests. These particular composite specimens were obtained from cutting historical bricks, built for each strengthening mortar and measuring $223 \times 57 \times 83\,mm^3$ (30 mm thick layer of mortar). Each mixed test piece was labelled with 'XL' where 'X' stands for the code of the relative mortar (A, B, C and D). Two composite test pieces for each mortar were subjected both to static and to cyclic loading tests and to freezing–thawing tests. These composite specimens were instrumented with three pairs of transducers (Figure 2), model W10TK manufactured by Hottinger Baldwin Messtechnik, with nominal run of 10 mm, working by variation of inductance. In this way, it has been possible to measure the individual axial deformations whose sum gives the volume deformation.

A high value was selected for the loading cycles (70% of the static load) in order to make the test severe enough despite the short duration of the test (100 000 cycles—1.3 Hz—~24 h) and to highlight the potential of several indicators monitored over time. Further experimental researches [4,10] confirm that the threshold of 70% is representative to test the durability of strengthening materials.

In analysing the volume deformation of the composite specimens, it has been assumed conventionally that negative values corresponded to extensions. Therefore, negative values in increasing of volume may reflect a lower degree of collaboration or even detachment phenomena between different materials [10].

2.2. Reinforced brickwork walls

In a second stage, on the basis of the experimental results of Section 2.1, the type of mortar D was chosen to continue the experimental campaign, increasing the composite brick–mortar specimen dimensions. A series of specimens consisting of reinforced brickwork walls (MR) by structural mortar D were manufactured, measuring $250 \times 250 \times 120\,mm^3$ (Figure 3) [11]. Static and cyclic loading were carried out by diagonal compressive test using an MTS (Material Testing Systems) machine with a closed-loop control. Freezing–thawing tests were also performed.

These tests were conducted in shear loading (Figure 3). In the first case, one specimen was tested up to failure in static condition after thermal cycles and one after fatigue cycles. In the second case, two elements were tested up to failure in fatigue tests without pre-damaging phase (Table I). Environmental actions were simulated on the reinforced specimen MR01 through freezing–thawing thermo-hygrometric cycles, subjected to eight thermal cycles. Each thermal cycle, extending for 25 h and characterised by

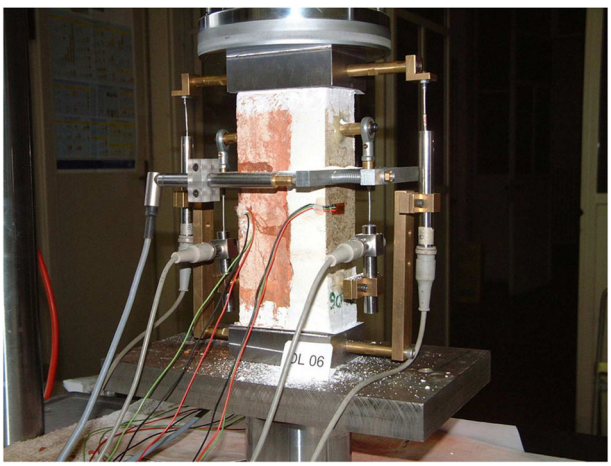

Figure 2. Instrumentation for composite brick–mortar test pieces.

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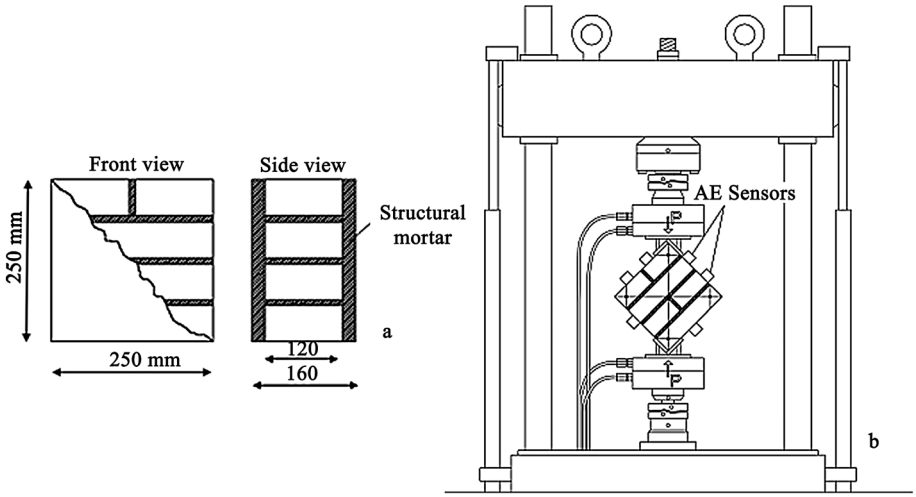

Figure 3. (a) Brickwork walls reinforced by structural mortar (MR). (b) Loading scheme, the specimen is tested in diagonal compressive condition using a servo-controlled machine (MTS).

Table I. Experimental programme of reinforced walls.

Specimen	Test 1	Test 2
MR01	Thermal (8 cycles)	Static (until failure)
MR02	Fatigue (10^5 cycles)	Static (until failure)
MR03	Fatigue (10^5 cycles)	Static (until failure)
MR04	Fatigue (until failure)	—

four different temperature levels (from −15°C to 60°C), was carried out using a laboratory oven. On the other hand, long-term loading behaviour was carried out through fatigue tests on reinforced specimen MR02 (Table I).

In this case, a value equal to 30% of the peak load (obtained by the previous static tests obtained in the following Section 3.1) was selected for the loading cycles. The duration of the pre-conditioning tests was about of 10^5 cycles—1 Hz—~24 h. After fatigue and thermal cycles, static shear tests were performed up to the peak load, under displacement control and at the rate of 10^{-3} mm/s on specimens MR01 and MR02.

Other two specimens, MR03 and MR04 were tested up to failure without the pre-conditioning phase (Table I). The test was conducted subjecting the walls to fatigue cycles up to failure by 50% of the peak load in order to evaluate the creep behaviour. The AE technique was also applied in order to evaluate the damage evolution. Every reinforced specimen was equipped by six AE sensors to detect the AE signal during the tests and by a couple of displacement transducers for each side (positioned along the two diagonals) in order to measure the horizontal and vertical displacements [11,12].

The ATEL measurement system used by the authors consists of piezoelectric transducers associated with control units, calibrated on inclusive frequencies between 50 and 500 kHz. The threshold level for the signals recorded by the equipment, fixed at 100 μV, is amplified up to 100 mV. The amplification gain, given by the relationship $\mathrm{dB} = 20\log_{10} E_u/E_i$, where E_u/E_i is the ratio between the input voltage and the output voltage, turns out to be 60 dB. The oscillation counting limit was fixed at 255 oscillations every 120 s [5–7].

The AE signals were received by the transducers applied to the surface of the structural elements. The leading-edge equipment adopted by the authors consists of six memory units USAM (Unit Stand Alone Memory) that can be synchronised for multi-channel data processing. The most relevant parameters acquired from the signals (frequencies in a range between 50 and 800 kHz, arrival time, amplitude, duration, number of events and oscillations) are stored in the USAM memories and then downloaded to a PC for a multi-channel data processing. Six piezoelectric transducers were glued with a silicone resin to the side faces of the test pieces.

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3. RESULTS ON SINGLE AND COMPOSITE TEST PIECES

3.1. Static and freezing–thawing tests

Compression tests were performed on single and mixed specimens in order to determine the main mechanical characteristics for all materials (Table II) and for all composite specimens (Table III).

The compression tests described in this section have only the aim to determine the principal mechanical characteristics of the single materials and the compression stress of the composite specimens.

3.2. Cyclic fatigue tests

In a typical $\varepsilon - N$ curve obtained from a cyclic fatigue test, we may discern three separate stages (Figure 4): stage I, where a fast increase in deformations occurs (10% of the test piece life); stage II, of stabilisation, where the deformations increase gradually at a nearly constant rate (10–80% of effective life) and stage III, displaying a rapid increment up to failure.

Several authors [13–15] demonstrated that the fatigue life of a material under cycling loading is closely correlated with the rate of growth of stage II deformations. By analogy with the method

Table II. Elastic modulus and compressive strength 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	4099	0.08	8.09	—

$\Delta\%\sigma$ is the percentage variation of the stress in the time.

Table III. Results of the 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

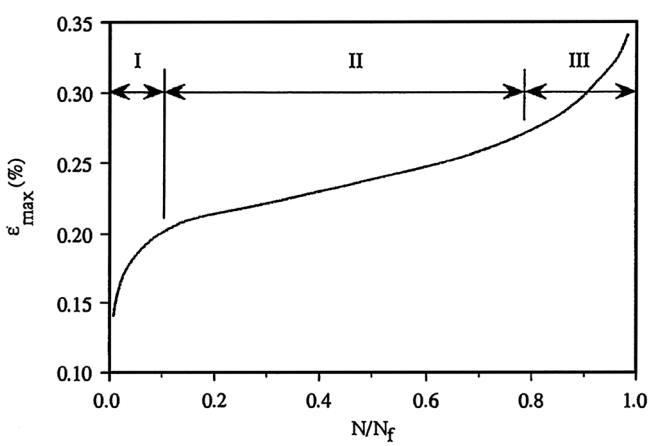

Figure 4. Typical deformation versus cycle number: $\varepsilon_v - N$.

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proposed for concrete, the evolution of longitudinal deformations over time is analysed as the primary parameter for quantifying and predicting material fatigue.

The goal is to ascertain whether the fatigue life of the mixed brick–mortar system also depends on the rate of increase of longitudinal deformations during stage II. Figure 6a–d show the vertical deformation on all mixed brick–mortar specimens tested to cyclic test. The test pieces that reached failure displayed a steeper slant in the stage II section of the curve followed, at ~80–90% of test piece life, by a sudden increase at stage III. Conversely, the curves obtained for the pieces that passed the 100 000 cycles displayed a lesser slant (Figure 5), reflecting an effective behaviour still far from the failure.

From the results of the cyclic tests, through linear interpolation between the 20% and 80% deformation values (secondary creep), the $\partial\varepsilon_v/\partial n$ derivatives were worked out, that is, the variations in the evolution of the deformation curve versus the time during stage II. Through a logarithmic scale linear regression, it is possible to chart the data to obtain an empirical relationship between the rate of variation of the vertical deformation $\partial\varepsilon_v/\partial n$ and the number of cycles s N_f at fatigue failure.

$$N_f = a\left(\frac{\partial\varepsilon_v}{\partial n}\right)^b \tag{1}$$

Equation (1) is a valid correlation between the stage II deformation variation rate $\partial\varepsilon_v/\partial n$ and fatigue life (given by the number of cycles at failure, N_f).

By performing a number of cycles on masonry specimens, up to the stage when the deformations grow at a constant rate, it is possible to forecast the a and b parameters of Equation (1) and therefore to predict fatigue life with a good degree of approximation [10,16]. From the linear regression on the analysed specimens, the parameters a and b are, respectively, worth 1839, 92 and −0, 7284. Through a case-by-case analysis, it is possible to determine how Equation (1), which is a function of the evolution of vertical deformations, is able to indicate the onset of a crisis in the brick–mortar system, preceding the final value of the test cycles.

3.3. Test pieces monitored by acoustic emission

In order to characterise the energy aspect of the materials during creep phenomena, individual test pieces sized $40 \times 40 \times 160\,mm^3$ and made of historical brickwork from the Royal Palace of Venaria were monitored with the AE technique during cyclic tests performed according the modalities described in Section 3.2. The employed procedure is referred to as ring-down counting, where the number of counts is proportional to crack growth. The exponential decay of this signal with respect to time, for a single cracking event, is shown in Figure 6. The number of counts (N) is obtained by determining the number of times that the signal crosses a certain threshold voltage. The crack growth

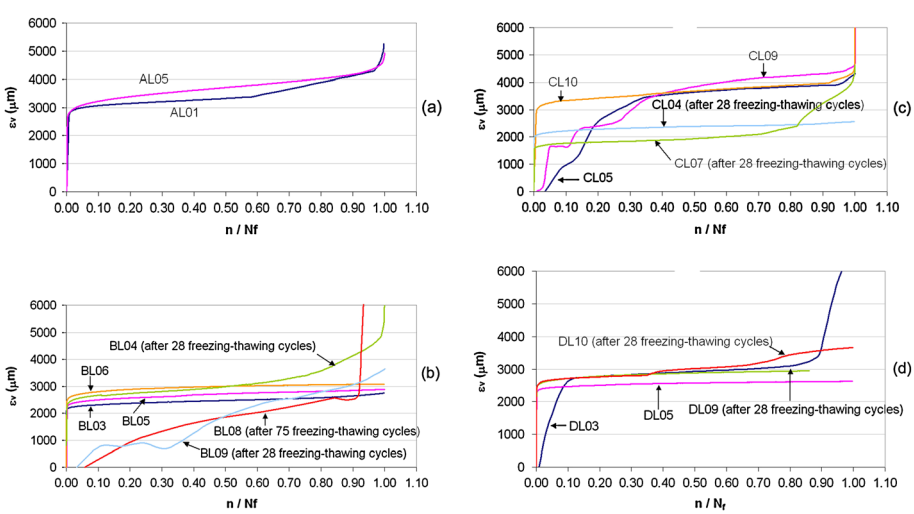

Figure 5. Cyclic loading tests on composite specimens: maximum vertical deformations.

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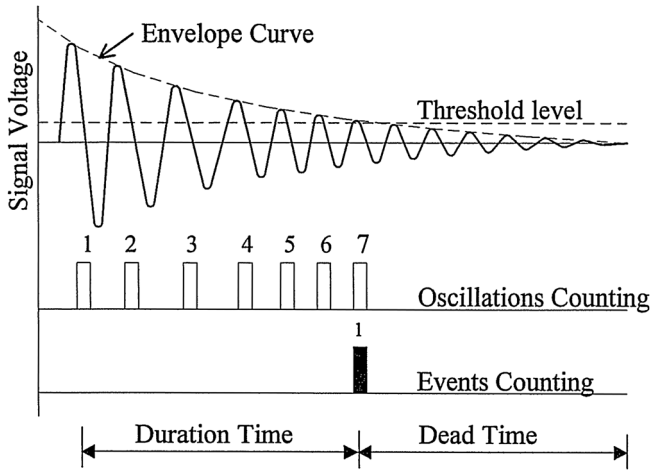

Figure 6. Signal identified by the transducer and counting methods in acoustic emission technique.

rate is related to the initial magnitude of the AE elastic wave. Utilising the ring-down counting method and neglecting the material attenuation properties, the AE counting number (N) can be assumed to be proportional to the quantity of energy released in the masonry units during the loading process [5–7].

In accordance with the findings described by other authors [15,17], it was possible to identify, also through the AE count, three distinct stages along the sequence leading to failure of the material under cyclic loading. In particular, the evolution of stage II can be viewed as an efficient indicator for the prediction of the fatigue life of the material.

A linear relationship between the AE counting number and the number of loading cycles was worked out from the tests. Figure 7 illustrates the typical evolution of the displacements (δ) recorded on a brickwork test piece under cyclic loading, characterised by three separate stages. In the same figure, the approximately linear evolution of the AE counting number versus the number of cycles is reported. It should be noted that up to point A, no energy is released in the form of elastic waves, because the material is in a stable stage (I) with virtually no microcracking events taking place inside it. After point A, the material begins to release energy as the first microcracks begin to form. This is a monitoring stage (stage II) during which the derivative of the deformations relative to the AE counting number remains constant. Yet, its value is a significant indicator for predicting the fatigue life of the material: the steeper is the slant of the stage II curve, the shorter will be the life of the material under fatigue loading.

To obtain a function similar to Equation (1) in terms of acoustic emissions, it is necessary to perform an experimental analysis on an appreciable number of test pieces. Using the ring-down counting

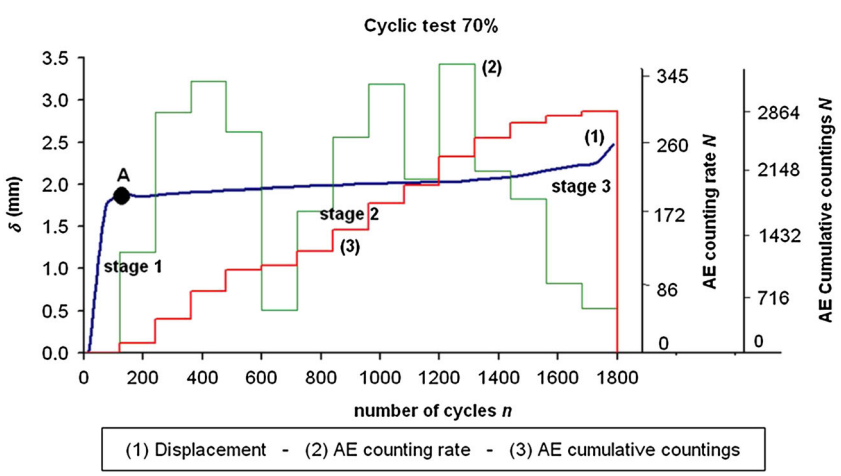

Figure 7. 70% cyclic loading test on brick specimens: monitoring by means of acoustic emissions.

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method, an expression would be obtained in the following form:

$$N_{\max} = c\left(\frac{\partial \varepsilon_{\mathrm{v}}}{\partial n}\right)^{\mathrm{d}} \tag{2}$$

where $N_{\max}$ is the AE cumulative counting number at the failure; c and d are the two constants to be experimentally identified. By means of the Equation (2), it is possible to forecast the fatigue behaviour of masonry specimens that are tested in laboratory, so as to determine the deformation changes in relation to the AE cumulative counting [18].

Using the Equation (2), it is possible to assess the fatigue life of the specimens through the cumulative number of AE signals. For this reason, it is possible to replace the cumulative number of AE signals to the number of cycles N_{f} introduced in the Equation (1). The hypothesis is that, considering the same level of strain ε, the cumulative number of the AE is proportional to the number of cycles N_{f}. If an ample experimentation was performed to verify Equation (2), also keeping in mind different scales of material, it would not be necessary to determine the strain ε of each specimens carried out on fatigue tests in order to analyse its critical conditions, but it would be enough to consider the total number of the AE to foresee the final failure [19].

4. RESULTS ON REINFORCED BRICKWORK WALLS

Many tests on masonry walls have been carried out, using diagonal compression loading, as shown in Figure 8a, to provide combined shear and compression on the mortar beds [11,20,21]. The recommendations of RILEM (1988) [22] and ASTM (1981) [23] describe an inclined compressive loading test in the masonry elements in order to estimate the diagonal tensile strength. The elastic theory, although strictly applicable to homogenous materials, can be used for uncracked masonry with only certain reservations [22]. The principal stresses, one compressive and the other tensile, are inclined by 45° to the longitudinal axis and the bed joint, respectively. The tensile stress generates a diagonal crack

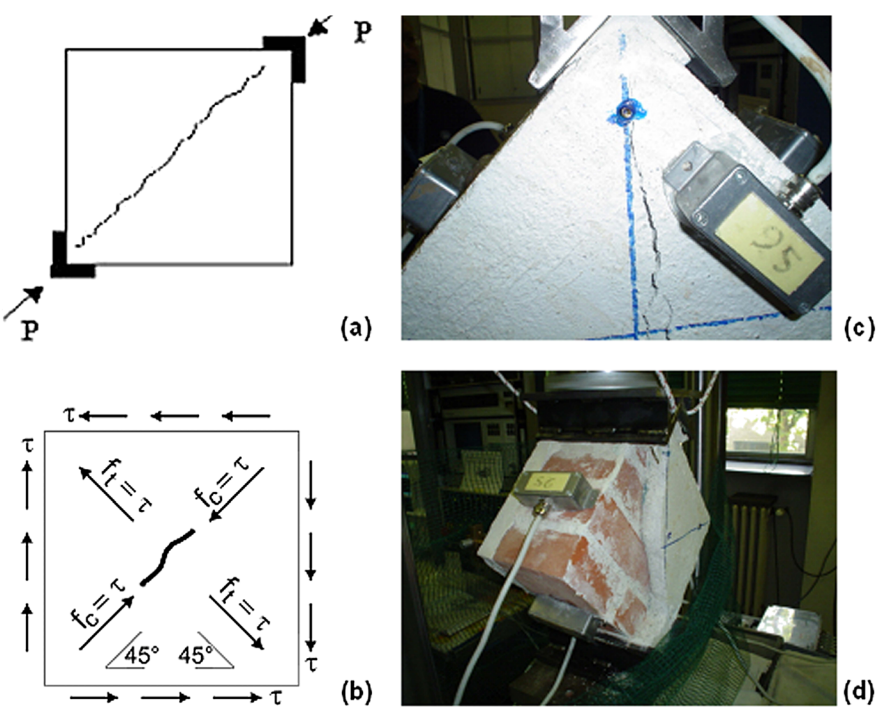

Figure 8. Loading scheme (a). Homogeneous element subjected to pure shear crack (b). Masonry specimen with mortar reinforcement, main diagonal crack (c) accompanied by a separation between the two mortar layers and brickwork surfaces (d).

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(Figure 8b). It can be noted that during laboratory tests, this diagonal crack is accompanied by a separation between the two mortar layers and the brickwork surfaces [11].

The ultimate shear stress and the shear strains in the static tests after pre-damaging cycles are considered. Figure 9 provides the sketch for calculating the stress and strain behaviour. In the figure, b is the lateral specimen length, t is the depth of the section, d is the diagonal length, δ_v is the vertical diagonal shortening and δ_h is the horizontal diagonal extension.

The shear stress τ can be calculated by [21]:

$$\tau = \frac{P}{\sqrt{2}bt} \tag{3}$$

Furthermore, considering the normal strains generated by the diagonal in-plane load as principal strains, the maximum shear strain γ_{max} can be computed as shown by the Mohr circle (Figure 9b):

$$\gamma = |\varepsilon_v| + |\varepsilon_h| = \left(\frac{|\delta_v| + |\delta_h|}{d}\right) \tag{4}$$

In Figure 10, the shear stress τ and the shear strain γ versus time are reported for the specimen MR02 in which the failure has occurred in static condition after the pre-damaging phase. It can be observed that the shear stress is equal to 1.4 N/mm^2. In the diagram of Figure 10b, the results are referred to the shear strain: the value of γ_{max} is equal to $4.2 \cdot 10^{-3}$. In Figure 10c, the τ versus γ behaviour is

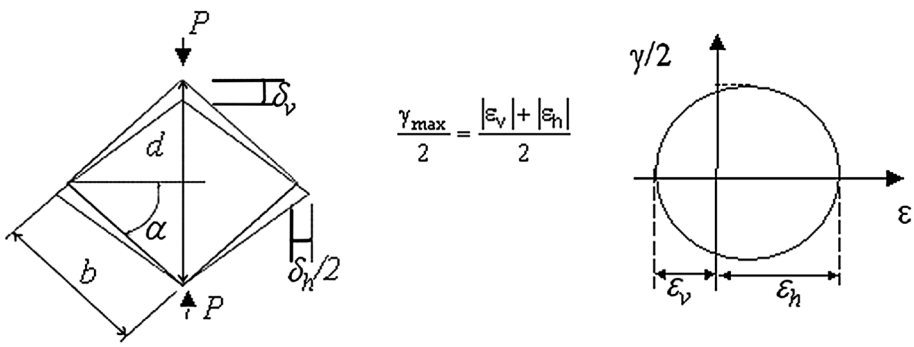

Figure 9. Generic shear strain definition sketch; for the tested specimen, α is equal to 45° (a). Mohr circle for the vertical (ε_v) and horizontal (ε_h) deformation (b).

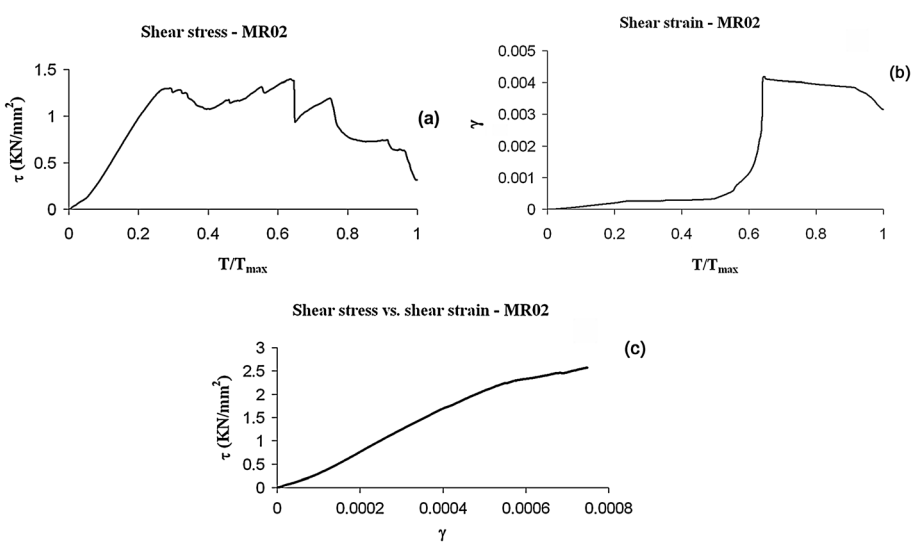

Figure 10. Shear stress (a) and strain (b) behaviour for the reinforcement specimen. Shear stress versus shear strain for mortar strengthening (c).

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shown. The graph is characterised by two clearly distinct phases. The first phase $0 \leq \gamma \leq 5 \cdot 10^4$ is characterised by a steepness branch of the curve. Further in the second phase, a sudden decrease of shear elastic modulus up to the ultimate strain is observed.

4.1. Application of the acoustic emission technique to static and fatigue tests

From AE signal elaboration, microcracks localisation is performed, and the condition of the monitored specimen can be determined [8].

4.1.1. Acoustic emission monitoring of strengthening masonry walls during static tests. For the specimens in which the rupture is reached through static tests (MR01-02-03), the load versus time and cumulative AE counting are depicted in Figure 11. These specimens all strengthened by structural mortar 'D' show a gradual decay and a ductile behaviour. The graphs show the cumulated number of AE events detected during the tests exceeding a certain threshold voltage. This counting is performed considering all signals perceived by AE sensor array during the tests. In the hardening branch of the load versus time curves, the cumulative counts increase proportionally to the load (Figure 11). This phenomenon has been verified because during the mechanical tests not all the energy employed by the test machine to deform the solid is represented in the load–time diagram. There is another quantity of energy that is dissipated for producing some new microcracks. This energy is proportional to the cumulative number of AE counts. In the specific test, in the hardening branch of the load versus time curve, the stored energy is proportional to the dissipated energy, which is the reason why the two curves, AE versus time and load versus time, are similar.

After the peak load, a further increase in the AE cumulated number is shown. The different cumulated number of AE counts observed in the different cases may depend on the level of corruption reached in the tested elements after several fatigue and thermal cycles and before the static tests. It can be noted in Figure 11a that, for the tests subjected to thermal fatigue cycles (MR01), an increase in the total number of AE events at the peak load is observed. This fact is due to a sort of hardening occurred in the strengthening mortar because of the thermal cycles before the static test, it is in line with results from [10,24].

4.1.2. Acoustic emission monitoring of strengthened masonry walls during fatigue cycle tests. Usually, the creep behaviour is obtained maintaining a constant load during the test. Another way to evaluate the creep phenomenon is to subject the specimens to fatigue tests. In this case, the specimen is subject to rapid and cyclic changes in the applied load [13–15].

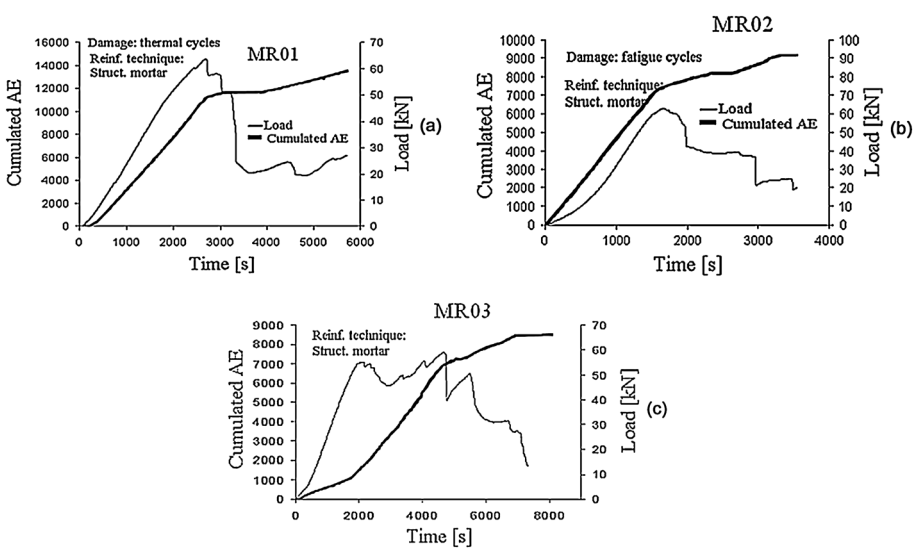

Figure 11. Load versus time and cumulated AE number. Mortar reinforcement after thermal cycles (a). Mortar reinforcement after fatigue cycles (b). Load versus time and cumulated AE number without pre-damaging phases (c).

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In the second phase of the experimental programme (Table I), fatigue tests are performed on specimens strengthened with structural mortar and conducted up to failure without a pre-damaging phase in order to evaluate the effect of creep behaviour. In this case, a value equal to 50% of the peak load (assumed on the basis of results derived from ad hoc tests) was selected for the loading cycles. The frequency of the load cycles was set to 2 Hz for each tested specimen. The number of cycles until failure is expected to be around $1.4 \cdot 10^5$.

In Figure 12, the shear strain behaviour and the AE counting number versus time are referred to MR04 specimen. The cumulative curve shows a behaviour very similar to that of a typical creep curve. In the first phase, a decreasing rate of γ, accompanied by a decrease in AE rate, can be noted. This first phase is in the intervals $0 \leq t/t_{\max} \leq 0.1$ for MR strengthening techniques. The second phase is characterised by a typical steady-state behaviour in the fatigue tests. In the third regime, an increasing slope is ever observed in the AE cumulative curve.

The time dependence of AE counting number N can be expressed as a power law [23]

$$N/N_{\max} = (t/t_{\max})^{\beta_t} \tag{5}$$

The β_t value assumes a very important meaning. For β_t lower than one, the damage growth is stable, this means that the specimen is in the primary phase far off the collapse conditions. For $\beta_t = 1$, the damage growth is metastable, and for $\beta_t \geq 1$, the damage growth is unstable, that is, the collapse is imminent in the tertiary phase (Figure 12). These three regions are indicated in Figure 12 and correspond to the three different values of exponent β_t. The increasing slope during the last stage of the test made it possible to indicate the beginning of the unstable damage growth and predicts the possible failure of the specimens at the 80% of $t/t_{\max}$. In this way, on the basis of the AE data collected in fatigue tests, the AE data analysis led to predict the time to failure of the masonry, taking into account the damage and the evolution of the cumulative AE number within the masonry over time [23,24].

5. CONCLUSIONS

The study of the long-term behaviour of historical masonry structures subject to creep is a factor of considerable importance in the assessment of damage levels in historical buildings, whether abandoned or severely damaged by seismic events. Also, the definition of appropriate strengthening works using materials having mechanical properties compatible with those of the original historical materials is a crucial theme for the durability of restoration work.

In the course of an extensive laboratory testing campaign, different types of test pieces, combining historical brickwork and strengthening mortar, were produced and subjected to cyclic compressive tests designed to accelerate the creep phenomena that occur under long-term static loads. Monitoring the deformation characteristics of the tested materials, by means of displacement transducers, and the energy aspect, by means of the AE technique, it is possible to analyse the material in a laboratory to forecast the fatigue life taking into consideration, in a classical way, the number of cycles N_f that leads to the rupture or evaluating the cumulative number of AE $N_{\max}$ that provides the released energy at the failure. The AE technique has proved effective in order to evaluate the damage evolution and the

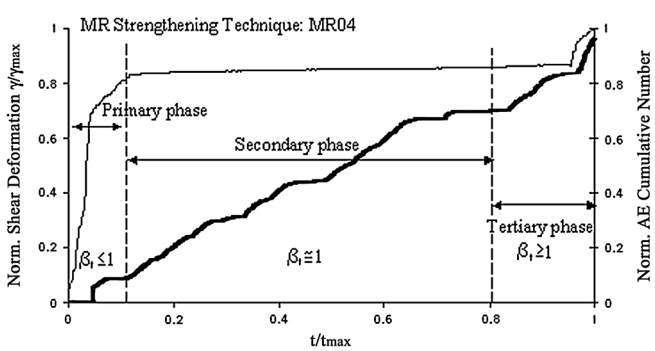

Figure 12. Cumulative AE and strain behaviour for specimen MR04.

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localization in static tests. This experimental methodology has shown his/her usefulness to qualify in a laboratory the durability of the strengthening materials to employ in the restoration work, taking into account the fatigue stress that can compromise the validity of repair work.

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