Reinforced masonry with FRP and structural mortar: durability evaluation by AE technique

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ABSTRACT: The aim of this work is to analyse and compare the shear resistance after long-term and environmental actions on brickwork structures reinforced by innovative or traditional techniques. To this end laboratory tests were carried out at the Non-Destructive Testing Laboratory of the Politecnico di Torino. In addition, the Acoustic Emission technique was employed to assess the damage localization, and the mechanical properties decay in order to evaluate the effectiveness of these rehabilitation methodologies.

1 INTRODUCTION

From a technological point of view, the strengthening of masonry structures has been accomplished adopting standard materials, mainly cement, concrete and steel, mortar, sometimes with the aim of changing the statics of the structures. Between these interventions, one of the most common method used to reinforce masonry structures is to provide single- or double-sided of mortar layers. Among these methodologies, the most innovative is certainly the reinforcement based on the application of Fiber Reinforced Polymer (FRP materials). Schwegler (1994) was the first to propose the use in laminates Carbon Fiber Reinforced Polymer (CFRP) as strengthening elements of masonry structures. In this work two different series of specimens are manufactured: the first series consists in brickwork walls reinforced by structural mortar (MR), the second one is reinforced by CFRP. Some of these specimens are previously exposed to thermal and mechanical cycles. To analyse the damage evolution into masonry elements during the tests, and to obtain information on the criticality of the ongoing process, the Acoustic Emission (AE) technique is used. The AE technique is a very effective non-destructive methodology useful to identify damage in masonry structures (Carpinteri & Lacidogna 2006a, 2006b, 2007). 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 in order to evaluate the damage evolution, and to localize damage crack sources (Carpinteri et al. 2006a, Anzani et al. 2007). In addition, the frequency domain is analysed and correlated to the failure evaluation with the changes arising in the signal power spectrum. The spectrum analysis is also used to investigate the signal frequencies that preceded the failure phase of the masonry elements.

2 EXPERIMENTAL PROGRAM

Two different series of specimens are manufactured: the first one consists in brickwork walls reinforced by structural mortar (MR), the second one is reinforced by Carbon Fiber Reinforced Polymer sheets (CFRP) applied on the external surfaces of the elements (Figs. 1a and b). The specimens measuring 250 x 250 x 120 mm^3 were tested up to failure in a shear test conditions. Environmental actions were simulated on MR and CFRP reinforced specimens (MR02 and MF02) through freezing-thawing thermo-hygrometric cycles. These specimens were subjected to 8 thermal cycles. Each thermal cycle, extending for 25 hours and characterized by four different temperature levels, was carried out using a laboratory owen. On the other hand, long-term loading behaviour was carried out through a fatigue test on both MR and CFRP reinforced specimens (MR03 and MF03). 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 duration of the tests was about of 10^5 cycles – 1 Hz – ca 24h. After these initial tests (fatigue and thermal cycles), shear tests were performed up to the peak load, under displacement control, at the rate of 10^{-3} mm/s (Fig. 1c). 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 in order to measure the horizontal and vertical displacements.

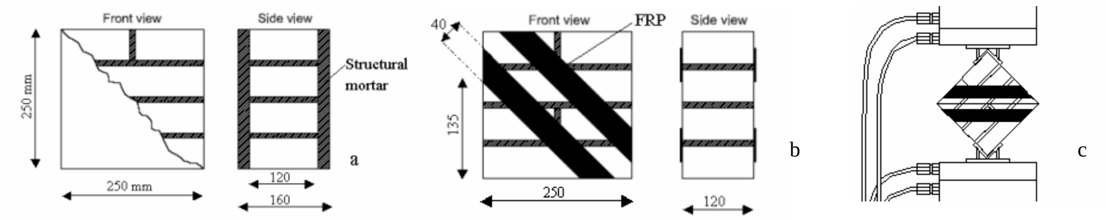

Figure 1. Brickwork walls reinforced by structural mortar (MR)(a). Brickwork walls reinforced by Carbon Fiber Reinforced Polymer sheets (CFRP) (b). Shear test under displacement control (c).

3 STRENGTHENIG TECHNIQUES AND FAILURE MODES

As mentioned above, a traditional methodology used to reinforce masonry structures is to provide single- or double-sided mortar layers. This technique is considered effective in increasing the strength, stiffness, and ductility of masonry walls. Many tests on masonry walls have been carried out, using diagonal compression loading, as shown in Figure 2a, to provide combined shear and compression on the mortar beds (Corradi et al. 2003; Gabor et al. 2006). The recommendations of RILEM (1988) and ASTM (1981) 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 (Marzahn 2002). 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 generate a diagonal crack (Fig. 2b). It can be noted that during laboratory tests, in the case of masonry specimens strengthened by double-sided mortar layers, this diagonal crack is accompanied by a separation between the two mortar layers and the brickwork surfaces. The failure mode changes considerably when the strengthening technique is performed by CFRP sheets applied externally as shown in Figure 1b. In this case, the failure does not occur through an inclined crack along the main diagonal because the transversal dilatation is confined by the CFRP reinforcement. The failure takes place through a *ripoff* mode (see CNR 2004) between the inner part of the masonry block and its surfaces where the CFRP sheets are applied.

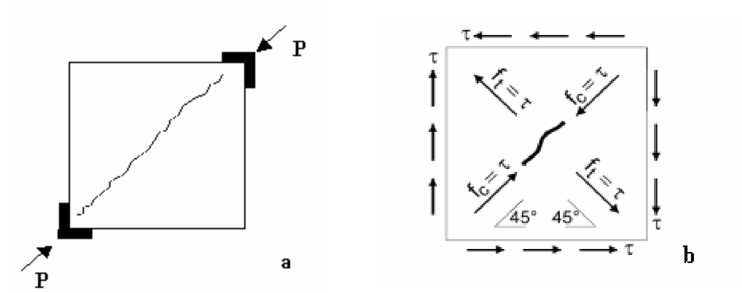

Figure 2. Loading scheme (a). Homogeneous element subjected to pure shear crack (b).

4 ACOUSTIC EMISSION MONITORING

The AE ultrasonic signals are analysed by a measuring system that counts the AE signals exceeding a certain voltage threshold. From this elaboration microcracks localisation is performed and the condition of the monitored specimen can be determined (Carpinteri et al. 2006a; Carpinteri et al. 2007). The AE signals can be received and recorded by transducers applied to the surface of the structural elements. The leading-edge equipment adopted by authors consists of six memory units USAM®, that can be synchronized 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 PZT transducers were glued with silicone resin to the side faces of the test pieces.

For the tested specimens, load vs. time and cumulative AE counting are depicted in Figure 3. In this Figure 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.

It can be seen that during the tests the cumulative counts increase proportionally to the load reaching their maximum value in the proximity of the peak load. The brickwork reinforced by CFRP shows the maximum number of cumulated AE events in the case where no thermal and mechanical cycles were performed (Fig. 3a, b). In all cases the shear resistance of the brickworks reinforced by CFRP is higher than that of the ones reinforced by structural mortar (see Fig.3).

The strengthening technique based on CFRP seems to be more effective than the reinforcement technique using structural mortar layers. These is confirmed for the specimens damaged by thermal cycles and for those affected by fatigue cycles. As a matter of fact, the peak loads reached for specimens strengthened by CFRP is ca 120 kN in both cases of thermal and fatigue cycles (see Figs. 3c, 3e). In the analogous cases, related to the specimens reinforced by structural mortar, the peak loads are ca 60 and 90 kN respectively (Figs. 3d, 3f). Moreover, the specimens reinforced by CFRP present a more brittle behaviour if compared with that obtained from the specimens reinforced by structural mortar. The CFRP reinforcement implies that, once the peak load is reached, an immediate decay of the resistance is observed, while the specimens strengthened by structural mortar show a gradual decay and a more ductile behaviour. In addition, in the case of specimens reinforced by structural mortar, in the last phase of the tests a further increase in the AE cumulated number is shown. Finally it can be noted that, for the tests subjected to fatigue cycles, a drastic reduction in the total number of AE events at the peak load is observed. As be shown in the next section, this behaviour is due to the fact that the specimens tested without fatigue cycles present the localized AE point sources prevailingly inside the material volume. On the other hand, the specimens tested after fatigue cycles present the localized AE sources at the interface between the reinforcement and the brickwork surfaces. The resistant mechanism is mainly due to confinement actions between the wall and the external reinforcements. The different cumulated number of AE counts observed in the different cases depends on the level of corruption reached in the tested elements after several fatigue and thermal cycles and before the static tests. In particular, it can be note that the specimen subjected to thermal cycles have a total number of events lower than the total number reached for specimens that are not subjected to damage cycles. This fact is due to the damage occurred in the specimens before the static tests. These elements have less energy to be dissipated during the static tests.

4.1 *Localization of AE sources*

Results of the localization procedure performed on four specimens are shown in Figure 4. In the figure two specimens are reinforced by external CFRP sheets (MF01 and MF03) and two by a double layer of structural mortar (MR01 and MR03). In particular, in Figure 4a and b the localization results are shown for two specimens reinforced by CFRP (a) and structural mortar (b); in this case no long-term or environmental actions are performed before the tests. As shown, the localization results are in good agreement with the cracking pattern. The same considerations can be made in the case of specimens MF03 and MR03. It can be observed that the AE point sources localized in the specimens, as expressed in Section 3, are mainly identified at the interface between the brickwork surfaces and the applied reinforcement. Furthermore, when the reinforcement adopted is a double layer of structural mortar, the localization shows a preferential rupture plane along the diagonal of the brickwork walls (MR01, MR03).

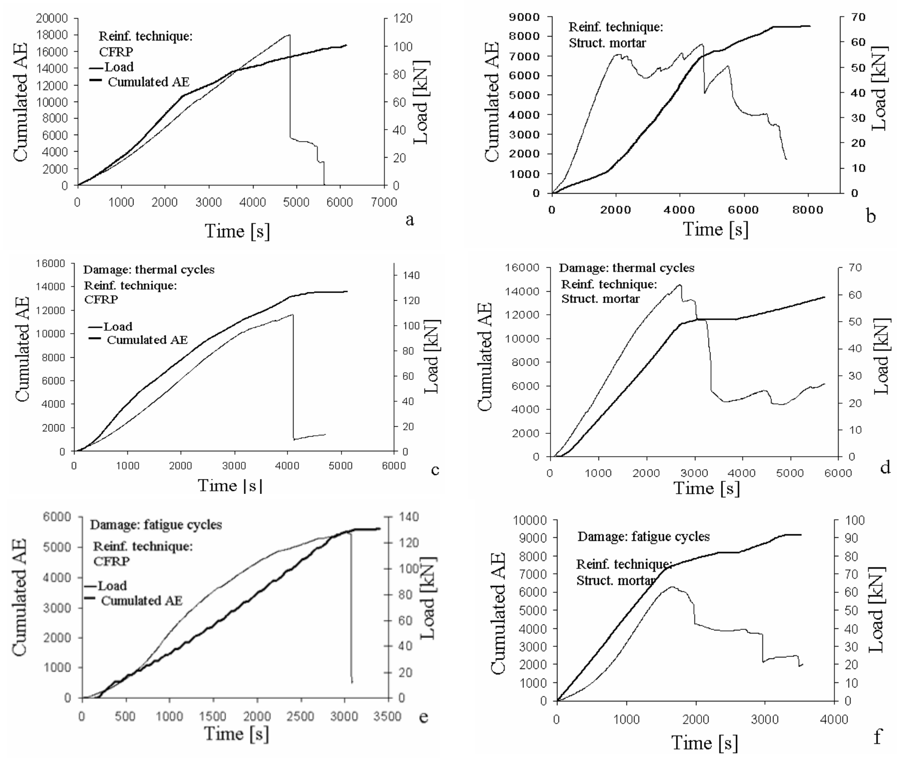

Figure 3. Load vs. time and cumulated AE number for both the reinforcement techniques: CFRP reinforcement (a). Structural mortar reinforcement (b). CFRP (c) and structural mortar reinforcement (d) after thermal cycles. CFRP (e) and structural mortar reinforcement (f) after fatigue cycles.

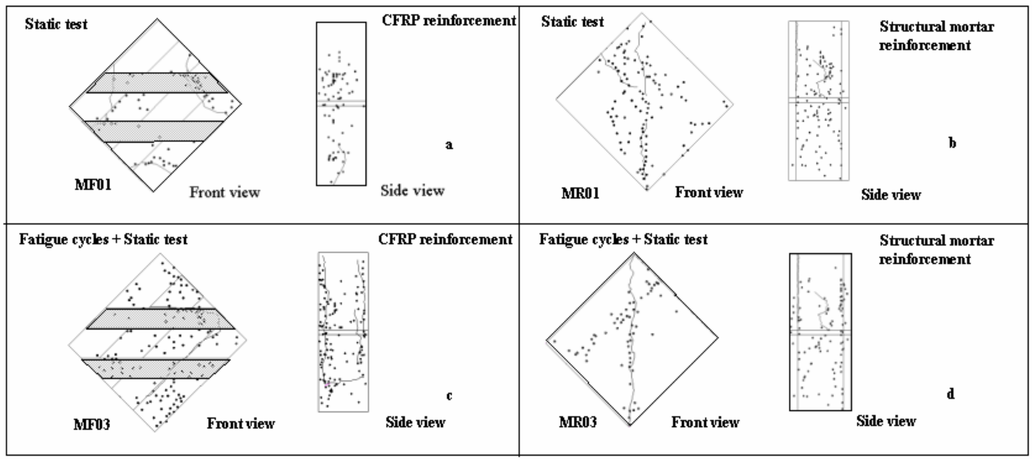

Figure 4. AE localization events in the case of brickwork walls reinforced by Carbon Fiber Reinforced Polymer sheets (CFRP) (a), (c) and structural mortar (b) and (d). No long-term or environmental actions (thermal or fatigue cycles) are performed before the static tests in specimens MF01 and MR01 (a), (b). Specimens MF03 and MR03 are previously subjected to fatigue cycles. (c), (d).

5. AE SIGNAL PROCESSING

The aim of this section is to analyse the AE signals recorded during the tests. By means of a frequency analysis of these signals, it is possible to follow the damage progress into specimens. As a matter of fact when damage increase the frequencies AE signals decrease. The results was been obtained on FRP reinforced specimen damaged with thermal cycles. During the experimental tests the amplification gain of the AE signals was selected to be 60 dB, with an input voltage of 100 μV. The impulsive waveform presented a peak of variable amplitude between 0.6 V and 6 V and a subsequent damping due to material attenuation. The noise threshold level during the test was evaluated in 0.5 V of the amplified signal. A time window (*T*) was chosen of 2×10^{-3} seconds (Fig. 5a). In order to analyse the AE signal frequency distribution, AE signal processing was performed. In this way, it was possible to relate during the tests the AE signals frequencies with the propagation of detected microcracks. Signal processing is based on spectral analysis by means of the Discrete Fourier Transform (DFT). AE signals were recorded with a sampling frequency of 2.5×10^3 kHz and the number of points in the time window *T* to evaluate the FFT is equal to 15×10^3. The obtained frequency spectrum range is between 0 and 1250 kHz. A simple procedure has been adopted in signal filtering by cutting the frequencies below 80 and above 800 kHz to eliminate the unwanted signal frequencies. This frequency range corresponds to the maximum sensivity range of the wide-band AE transducers. Typical result are shown in Figure 5b, where the amplitude spectrum is normalized.

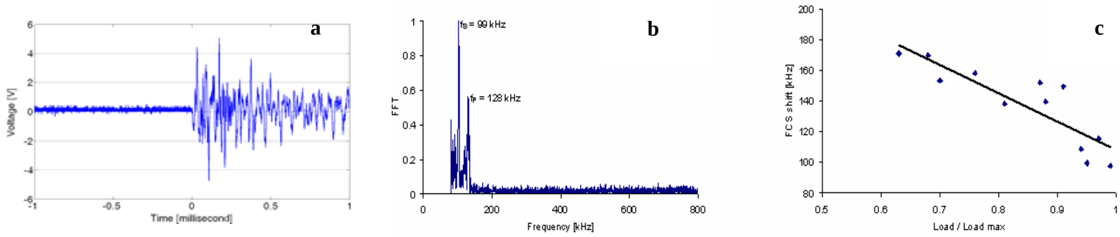

Figure 5. FRP reinforced specimen damaged with thermal cycles. AE signal (a). AE frequency spectrum filtered by cutting the frequencies below 80 and above 800 kHz (b). FCS shift vs. normalized load obtained during the test (b).

Two response peaks are shown in Figure 5b. We assume that the second peak represents the longitudinal wave (*P*-wave) and the first is related to the shear wave (*S*-wave) (Shah & Li 1994). For FRP reinforced specimen damaged with thermal cycles, the frequency *P*-wave is ~ 130 kHz, while the frequency *S*-wave is ~ 100 kHz. It is interesting to note that these frequencies are different from the findings of Shah and Li (1994). They found in concrete a mean frequency of 100 and 350 kHz for the *S*-wave and *P*-wave, respectively. Moreover, other authors (Reymond 1978; Labuz et al. 1987; Kim 1989) reported observations in a frequency range between 250 and 500 kHz for rocks and concrete analysed by acoustic emission. The difference from these results, can be explained considering that the masonry attenuation is greater than in concrete and rocks. When damage increases, changes in the shape of AE frequency spectra are observed. These changes reflect the variations in the material attenuation during the tests. For this reason, it is possible to apply the method of moments (Kiernan & Duke 1990; Talreja 1988) in order to evaluate a frequency spectrum parameter, namely the Frequency Centroid Spectrum (FCS):

$$FCS = \int_{f1}^{f2} P(f) \cdot f \cdot df \Big/ \int_{f1}^{f2} P(f) \cdot df \qquad (1)$$

In Equation 1, the variable *f* is the frequency and *P*(*f*) is the power spectrum. In the present paper, the AE signal frequency range is between 80 and 200 kHz, and the selected limits *f1* and *f2* are equal to the mentioned frequencies values. By the evaluation of FCS at several steps of the test, it is possible to observe a FCS shift toward lower frequencies. High AE frequency can be associated to the yield of small cracks. When these cracks coalesce into flaws of increasingly larger size, the AE release lead to lower frequency. For the FRP reinforced specimen damaged with thermal cycles, the frequency decay vs. applied load is shown in Figure 5c. In this Figure, the AE frequency decay is shown through the best fitting line. It can be observed that the FCS shift changes from 171 to 98 kHz. Similar trends are obtained also for the other masonry specimens. These results imply that the AE frequencies decay can be assumed as a valid indicator of the damage evolution in reinforced masonry elements subjected to shear conditions.

6 CONCLUSIONS

An experimental laboratory research to evaluate the durability on reinforced masonry walls through thermal and fatigue cycles is presented. Two brickwork specimens sets was reinforced with two different techniques: an innovative technique, the CFRP sheets, and a more traditional technique, the strengthening mortar. The AE technique has proved effective in order to evaluated the damage evolution and crack localization. In addition, the AE signal frequency domain is analysed and correlated to the failure evaluation with the changes arising in the signal power spectrum.

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