Frequency Analysis of Acoustic Emission Signal to Monitor Damage Evolution in Masonry Structures

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Abstract. A crucial aspect in damage evaluation of masonry structures is the analysis of long-term behaviour and for this reason fatigue analysis has a great influence on safety assessment of this structures. Acoustic Emission (AE) are very effective non-destructive techniques applied to identify micro and macro-defects and their temporal evolution in several materials. This technique permits to estimate the velocity of ultrasound waves propagation and the amount of energy released during fracture propagation to obtain information on the criticality of the ongoing process. By means of AE monitoring, an experimental analysis on a set of reinforced and unreinforced masonry walls under variable amplitude and static loading has been carried out. During these tests, the AE signals were recorded. The AE signals were analysed using Fast Fourier Transform (FFT) to examine the frequency distribution of the micro and macro cracking. It possible to evaluate the evolution of the wavelength of the AE signal through the two characteristic peak in the AE spectrum signals and the wave speed of the P or S waves. This wavelength evolution can be represent the microcrack and macrocrack evolution in masonry walls. This procedure permits to estimate the fracture dimension characteristic in several loading condition and for several masonry reinforced condition.

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. This technique is considered effective in increasing the strength, stiffness, and ductility of masonry buildings [1,2]. On the other hand, among these methodologies, the most innovative is certainly the reinforcement based on the application of Fiber Reinforced Polymer (FRP materials). Schwegler [3] was the first to propose the use in laminates Carbon Fiber Reinforced Polymer (CFRP) as strengthening elements of masonry structures. He developed an analytical model for the in plane behaviour of CFRP strengthened walls. The wide use of FRP materials induces to focus on the durability of the bond between the reinforcement and the support in several mechanical and environmental conditions that influences the effectiveness of the technique.

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) applied on the external surfaces of the elements. Some of these specimens are previously ex-posed to thermal and environmental conditions.
mechanical cycles with the aim to simulate the in-situ conditions. 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 defects and damage in masonry structures [4,5,6,7,8]. 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. In addition, the frequency domain is analyzed 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 were tested up to failure in a shear test conditions. The long-term loading behaviour was carried out through a fatigue test on both MR and CFRP reinforced specimens. In this case a value equal to 50% of the peak load (assumed on the basis of results derived from ad hoc static tests) was selected for the loading cycles. The cyclic tests were conducted using a servo-controlled machine (MTS) with a closed-loop control. The test arrangement is shown in Figure 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.

Table 2. Brick, Bed and Structural Mortar mechanical parameters

| Mechanical parameters [MPa] | Brick | Bed Mortar* | MR Reinforced Mortar* | CFRP material |
|-----------------------------|-------|-------------|-----------------------|--------------|
| Compression Strength        | 16    | 7.5         | 18                    | -            |
| Elastic Modulus             | 11·10³| 16·10³      | 230·10³               | 2.5·10³      |
| Tensile strength            | -     | -           | -                     | -            |

3. Strengthening techniques and failure mode

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 [9,10]. The recommendations of RILEM [11] and ASTM [12] 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 [13]. 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 (see Fig. 2a, b and d). 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) [14] between the inner part of the masonry block and its surfaces where the CFRP sheets are applied (Figs. 2e and f).
Figure 1. Brickwork walls reinforced by structural mortar (MR) (a). Brickwork walls reinforced by Carbon Fiber Reinforced Polymer sheets (CFRP) (b). Servo-controlled machine (MTS) with a closed-loop control and loading scheme (c).

Figure 2. 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). Masonry specimen with CFRP reinforcement, the failure takes place through a ripoff mode between the inner part of the masonry block and its surfaces where the CFRP reinforcements are applied (e) and (f).
4. Acoustic Emission monitoring

Analysing a structure by means of the AE technique, it proves possible to detect the occurrence and evolution of stress-induced cracks. Cracking, in fact, is accompanied by the emission of elastic waves which propagate within the bulk of the material. The AE ultrasonic signals are analysed by a measuring system that counts the AE signals exceeding a certain voltage threshold. The leading-edge equipment adopted by authors consists of many units USAM® that can be synchronized for multi-channel data processing (Figure 3). The most relevant parameters acquired from the signals (arrival time, amplitude, duration, number of events and oscillations) are stored in the USAM memory and then downloaded to a PC for a multi-channel data processing. To detect the AE signals six PZT transducers were glued with silicone resin on the external surfaces of the test specimens.

![Figure 3. Acoustic emission measurement equipment.](image)

5. Acoustic Emission signal processing

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 was chosen of 2 x 10^{-3} seconds (Fig. 4).

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). DFT is the primary tool of digital acoustic signal processing. The foundation of DFT is the Fast Fourier Transform (FFT), a method for computing the DFT with reduced execution time [15]. Spectral analysis was performed through the technical computing software MATLAB®, which provides the functions of direct and reversed spectral transformations to compute the DFT. AE signals were recorded with a sampling frequency of 2.5 x 10^3 kHz and the number of points to evaluate the FFT is equal to 15 x 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 sensitivity range of the wide-band AE transducers. A typical result is shown in Figure 5, where the amplitude spectrum is normalized.

![Figure 4. Typical Acoustic Emission signal recorded during the tests.](image)

![Figure 5. FRP reinforced specimen damaged with thermal cycles. AE frequency spectrum filtered by cutting the frequencies below 80 and above 800 kHz.](image)
Two response peaks are shown in Figure 5. We assume that the second peak represents the longitudinal wave (P-wave) and the first is related to the shear wave (S-wave). The P-wave is in a central frequency of \(~ 130\) kHz, while the S-wave is in a central frequency of \(~ 100\) kHz. It is interesting to note that these frequencies are different from the findings of Shah and Li [16]. They found in concrete a mean frequency of 100 and 350 kHz for the S-wave and P-wave, respectively. Moreover, other authors [17,18,19] 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.

The frequency decay with regard to the damage evolution in solid media can be explain by means of a sample physics analogy: the pendulum principle. The frequency \(f\) of the pendulum is in inverse relation to its length \(l\): \(f^{-1} = 2\pi (l/g)^{1/2}\). As soon as the size of the crack increase, either due to the enlargement of one previous crack, or the coalescence of several previous smaller crack (or both), the AE shall correspondingly become of progressively lower frequency, until leaving the ultrasonic range and reaching the sonic range, which is the well-know seismic roar. This fact is the same of the seismic phenomena.

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 [20,21] in order to evaluate a frequency spectrum parameter, namely the Frequency Centroid Spectrum (FCS) (Figure 6):

\[
FCS = \frac{\int_{f_1}^{f_2} P(f) \cdot f \cdot df}{\int_{f_1}^{f_2} P(f) \cdot df}
\]

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 \(f_1\) and \(f_2\) 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. For the FRP and mortar reinforced specimen damaged with fatigue cycles, the frequency decay vs. applied load is shown in Figure 7. It can be observed that the FCS shift changes from 0.3 to 0.9 of the FCS maximum.

This frequency parameter highlights the different failure mechanisms for two strengthening techniques. As a matter of fact, for mortar reinforced specimen the behaviour is ductile with a diffuse crack in all volume of the masonry wall. For FRP reinforced specimen a brittle behaviour is observed with a not too extensive damage evolution except for the final test steps when the failure of the specimen is reached. This fact is marked by the two linear slope interpolation.

The main goal of this work is to evaluate the evolution of the crack dimension by means of a signal parameter. This one is the wavelength \(\lambda\) as a function of the shear velocity \(V_s\) and its frequency \(f_s\). \(\lambda\) is defined as:

\[
\lambda = \frac{V_s}{f_s}
\]

Shear velocity wave is a function of:

\[
V_s = \sqrt{\frac{G}{\rho}}
\]
where $G$ is the concrete stiffness and $\rho$ is the mass density of the material. In this work $V_s$ is fixed and the $S$-wave frequency vary with the damage evolution. During the test, for each AE signal recorded is possible to evaluate the AE spectrum with the procedure illustrated in the previous paragraph. In this way it is possible to calculate the $S$-wave frequency characteristic.

![Figure 6](image_url)

**Figure 6.** An example of two AE spectrum in two several step of the shear test on FRP reinforced specimen: it is important to observe the shift of the FCS towards the lower frequencies during the test.

![Figure 7](image_url)

**Figure 7.** FCS shift vs. time for specimens MF and MR

In Figure 8 is possible to observe the shear deformation curve (dashed, dotted and continuous line) and the evolution of wavelength (square points, circle points and triangular points) versus test time for mortar reinforced masonry specimens (Fig. 8a) and CFRP reinforced masonry specimens...
(Fig. 8b). The fracture process under cyclic loading conditions is different between mortar and CFRP reinforcement specimens. A gradual evolution of the dimension of the crack is observed for mortar reinforced masonry specimens; a suddenly increase of the wavelength (i.e. crack dimension) is observed before the fatigue collapse of the specimens. In other words, a gradual fracture growth is observed and the coalescence of the microcrack leads to the final macrocrack pattern. As a result, in the final step of the test it is easy to observe, a marked diagonal crack with the separation of the mortar layer by the masonry support. For CFRP reinforced masonry specimens, a constant trend is observed for the whole test duration. Only before the failure of the specimens, a rapidly increase of the wavelength is shown. This fact means that the CFRP reinforcement specimens shown the absence of the fracture growth during the test: only before the collapse, it possible to observe fracture signs on the face of the masonry walls; this fact confirm the brittle behaviour of the masonry walls reinforced with CFRP sheets. This fact confirms that the \( \lambda \) parameter can be considered as a precursor of the structural collapse.

6. Acoustic Emission signal processing

An experimental laboratory research to evaluate the durability on reinforced masonry walls through 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. In addition, the AE signal frequency domain is analyzed and correlated to the failure evaluation with the changes arising in the signal power spectrum.

The method shown represents an innovative application based on the definition to the signal parameter \( \lambda \) able to represent the evolution of the fracture dimension in the masonry structures during the fracture process and hence to monitor the damage evolution during the life structures.

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Figure 8. Shear deformation ($\gamma$) and wavelength ($\lambda$) vs. time ($t$) for mortar reinforced masonry specimens (a) and CFRP reinforced masonry specimens (b) (MF01 dashed line and square points, MF02 dotted line and circle points, MF03 continuous line and triangular points; MR01 dashed line and square points, MR02 dotted line and circle points, MR03 continuous line and triangular points)