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Characterization of debonding in FRP-strengthened masonry using the acoustic emission technique

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ABSTRACT

The acoustic emission (AE) technique is used for investigating the interfacial fracture and damage propagation in GFRP- and SRG-strengthened bricks during debonding tests. The bond behavior is investigated through single-lap shear bond tests and the fracture progress during the tests is recorded by means of AE sensors. The effect of hygrothermal conditions on the debonding characteristics and failure mode is also investigated by performing accelerated ageing tests. Accelerated ageing tests resulted in a change of failure mode in GFRP-strengthened specimens which helped in assessment of AE output in different failure modes, but no conclusive strength degradation was observed in the specimens. The results show that the average and cumulative AE energy are correlated to the FRP slip and debonding fracture energy in GFRP-strengthened specimens, respectively. The fracture progress and active debonding mechanisms are characterized using results from the AE technique. Moreover, a clear distinction between the AE outputs of specimens with different failure modes, in both SRG- and GFRP-strengthened specimens, is found which allows characterizing the debonding failure mode based on acoustic emission data. The tests performed in this study are also a contribution towards the application of AE techniques for on-site health monitoring of strengthened masonry structures.

1. Introduction

The application of composite materials, such as Fiber Reinforced Polymers (FRPs) and Steel Reinforced Grouts (SRGs), for Externally Bonded Reinforcement (EBR) has gained increasing interest during the last years. Advantages such as low weight to strength ratio and flexibility in application have made FRPs an efficient solution for strengthening purposes. The use of steel fibers with inorganic matrices (e.g. SRGs) adds compatibility to the above mentioned advantages, providing new developments in durable strengthening of historical heritage and masonry structures [1].

The effectiveness of EBR techniques is intrinsically dependent on the bond behavior between the composite material and the masonry substrate. Therefore, understanding the involved stress transfer and fracture progress is crucial for design purposes. On the other hand, development of qualitative and quantitative bond assessment methods is necessary for structural health monitoring purposes. Significant progress has been achieved in the last years regarding experimental investigation and computational modeling of the debonding phenomenon and damage in FRP-strengthened masonry elements [1–4]. However, aspects such as failure initiation, interfacial damage propagation and localization, as well as nondestructive bond quality monitoring are still open. This paper shows how these aspects can be monitored and characterized by means of acoustic emission (AE) technique during experimental testing. A relation between the AE output and bond characteristics such as force-slip behavior, fracture energy, active failure mechanisms and debonding propagation provides valuable information for bond behavior assessment and numerical modeling purposes. The tests performed in this study are also a contribution towards the application of AE techniques for on-site health monitoring of strengthened masonry structures.

The AE technique has been extensively used for real time detection of internal damage propagation in structural elements [5–10]. In this technique, piezoelectric sensors are used to detect high-frequency mechanical waves produced from the release of strain energy during fracture and crack propagation. It has been found

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that the AE outputs are valuable in understanding crack propagation and failure mode in laboratory tests. These findings have also made this technique interesting for on-line structural health monitoring.

The current study addresses the use of the AE technique in investigating the fracture process during the debonding phenomenon in masonry elements strengthened with composite materials. Single-lap shear bond tests have been performed on strengthened bricks and the interfacial fracture during the debonding tests has been monitored with AE sensors attached to the bricks' surface. Solid cay bricks were used as the substrate, while Glass Fiber Reinforced Polymer (GFRP) and Steel Reinforced Grout (SRG) composites were used as the strengthening materials. GFRP composites, compared with other conventional FRP materials, have lower axial stiffness which makes them more suitable for masonry structures [2]. However, durability of this strengthening technique is still under investigation. SRG has been chosen as a composite material with inorganic matrix that can be advantageous for strengthening masonry structures regarding compatibility and sustainability issues [1]. The effect of environmental conditions on the debonding phenomenon and failure modes has also been investigated in the presented study by performing accelerated ageing tests on a number of specimens before performing the debonding tests. The results obtained from the shear bond tests and the AE data are next presented and discussed.

2. The acoustic emission technique

2.1. General description and methodology

Acoustic Emissions (AEs) are high-frequency transient elastic waves that are emitted within the material during local stress redistributions such as micro-crack growth. These emissions are detected on the material's surface by means of piezoelectric transducers, pre-amplified, filtered and amplified before being sent to the data logger. The technique has the advantage over other damage detection techniques that it relies on detection of information which is generated by the fracture process itself and allows for online damage detection and assessment [11].

A typical AE transient is presented in Fig. 1. Background noise is eliminated through setting a minimum amplitude threshold. An AE hit with a predefined duration is recorded when the threshold is exceeded. For each AE hit, a number of parameters (e.g. arrival time, amplitude, count, duration and energy) and the waveform itself are recorded. The amount of detected AE hits and energy is influenced by the hardware used and software settings, thus software defined parameters (e.g. threshold and sampling frequency)

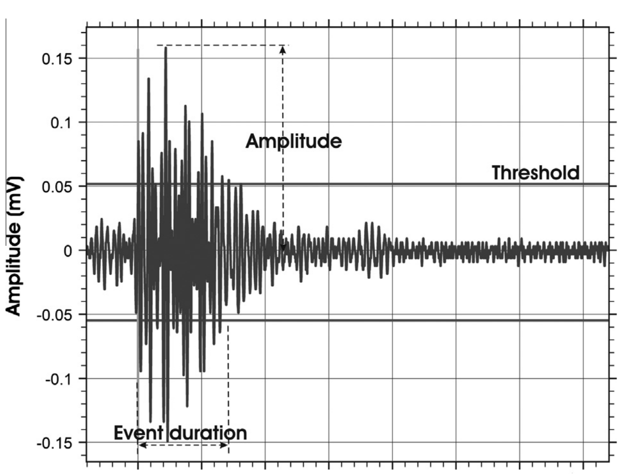

Fig. 1. Typical AE transient event with indication of wave characteristics.

should be kept constant for subsequent tests. The detection of acoustic emissions is also sensitive to a number of setup-specific boundary conditions, such as quality of the coupling between sensor and test specimen, attenuation and speed of wave propagation, source-sensor distance, specimen size and homogeneity.

The recorded acoustic emissions hold information on the fracture process that produced them. Basic AE hit counting, taking into account the cumulative or average number of AE hits, or emitted AE energy, has successfully been used for damage assessment in rock, concrete and masonry [5,12]. Other wave properties, such as amplitude or number of threshold crossings (counts) are also used for parameter-based analysis [5,13]. It is generally observed that micro-cracks generate a large amount of small amplitude emissions, while AE emissions from macro-cracks are fewer but have higher amplitude. Based on this observation, the *b*-value is applied in seismic analysis to characterize the fracture process by means of the slope of the amplitude distribution [14]. Instead of the seismic *b*-value, an improved *b*-value (*Ib*-value), in which the number of AE data taken into account is set before calculation, is usually applied for AE applications in concrete and rock [15,16].

More advanced signal-based analysis takes into account the complete AE signal allowing characterization of the fracture modes [5,17]. High sampling rates and the use of broadband AE sensors are required for this technique. But dedicated signal processing and interpretation can become time-consuming for large data sets. Signal-based analysis has limited application in concrete and masonry, due to the high attenuation and disturbance of the AE wave caused by the heterogeneity of the material, especially in case of masonry. As a compromise between both approaches, a simplified signal-based analysis can be applied, using the RA value and frequency to characterize the fracture process. The RA value is calculated from the ratio of the rise time (time interval between triggering time of AE signal and maximum amplitude) and the maximum amplitude. Lower average frequencies and higher RA values indicate a shift from tensile to shear nature of fracture processes [18,19]. Recent numerical and experimental studies have shown that the reliability of crack classification depends on the homogeneity of the material and the distance between source and sensor [20]. Heterogeneities, such as aggregates in concrete, nucleation of cracks or brick-mortar interfaces in masonry, cause dispersion and consequently alteration of the waveform. As masonry is a highly heterogeneous material, crack characterization should be performed carefully taking into account these issues.

In this paper, it is shown that average and cumulative AE energy can be applied to characterize debonding phenomenon in strengthened masonry bricks when a limited number of resonance AE sensors are used.

2.2. AE technique for detection of FRP debonding

FRP debonding from masonry substrate can be accompanied by failure of the bricks, debonding in the brick-adhesive interface, debonding in the fiber-mortar interface (in case of SRG) and subsequent pull-out of the fibers or a combination of these fracture processes. In the present study, these failure mechanisms were observed in real time and characterized by means of AE detection. In literature, AE monitoring during FRP debonding from concrete beams and slabs was studied by Carpinteri et al. [21] and by Degala et al. [7], while shear behavior of strengthened masonry walls was analyzed by Antonaci et al. [22].

3. Experimental program

The experimental study focuses on detection of the interfacial damage during debonding in strengthened masonry bricks by