Acoustic emission and numerical analysis of the delamination process in repair plasters applied to historical walls

Elsevier Editorial System(tm) for Construction & Building Materials
Manuscript Draft

Manuscript Number: CONBUILDMAT-D-19-06940R1

Title: Acoustic emission and numerical analysis of the delamination process in repair plasters applied to historical walls

Article Type: VSI:Damage detection, ICEM18

Keywords: historical walls; repair plaster; acoustic emission; plaster delamination; laboratory test; fracture mode; stick-slip behavior.

Corresponding Author: Dr. Alessandro Grazzini, Ph.D.

Corresponding Author's Institution: Politecnico di Torino

First Author: Alessandro Grazzini, Ph.D.

Order of Authors: Alessandro Grazzini, Ph.D.; Federico Accornero, Ph.D.; Giuseppe Lacidogna, Professor; Silvio Valente, Professor

Abstract: The delamination process of plasters applied for the repair work of historical walls was often caused by humidity phenomena or physical-mechanical cycles stress. In this paper a new experimental methodology has been conducted by testing in the laboratory mixed stone-mortar specimens and analyzing the delamination progression. The experiment simulated the recurring delamination in the stone walls of the Sacro Monte di Varallo, an UNESCO site in Piedmont (Italy). Through the monitoring by means of acoustic emission (AE) sensors during the tests it was possible to qualify the different fracture modes characterizing the delamination process, which takes place during the tests at the interface between plaster mortar and stone block. AE is a non-destructive technique useful to estimate the amount of energy released from fracture propagation in the adherence surface between mortar and stone. The experimental results confirmed the stick-slip behaviour that characterises the friction process inside the delamination surface between repair mortar and masonry stone.

Cover Letter for the paper:

“**Acoustic emission and numerical analysis of the delamination process in repair plasters applied to historical walls**”

by Alessandro Grazzini, Federico Accornero, Giuseppe Lacidogna, Silvio Valente.

Dear Editor,

in this manuscript the delamination process of plasters applied to the repair works of historical walls is treated.

A new experimental methodology has been conducted by testing in the laboratory mixed stone-mortar specimens to analyze the delamination process, which is often caused by humidity phenomena or physical-mechanical cyclic stresses.

Notably, the delamination process recurring in the stone walls of the "Sacro Monte di Varallo", an UNESCO site in Piedmont (Italy), has been simulated by the aforesaid experiments.

Through the monitoring by means of acoustic emission (AE) sensors, it was possible to qualify the different fracture modes characterizing the delamination process, which takes place during the tests at the interface between the plaster mortar and the stone block.

The experimental results confirmed the stick-slip behaviour that characterises the friction process on the delamination surfaces between repair mortar and masonry stone.

I hope that this paper will be of interest to the readership of Construction & Building Materials SI “Damage Detection, ICEM18”, and especially those who deal in historical walls, repair plaster, plaster delamination, acoustic emission, fracture mode and stick-slip behavior.

With my best regards,

Alessandro Grazzini, PhD

Politecnico di Torino - Italy

***Conflict of Interest**

ACOUSTIC EMISSION AND NUMERICAL ANALYSIS OF THE DELAMINATION PROCESS IN REPAIR PLASTERS APPLIED TO HISTORICAL WALLS

Alessandro Grazzini, Federico Accornero, Giuseppe Lacidogna, Silvio Valente

Politecnico di Torino (Italy)

There are no conflicts of interest in the contents of this paper.

Acoustic emission and numerical analysis of the delamination process in repair plasters applied to historical walls

Alessandro Grazzini[1 *], Federico Accornero[1], Giuseppe Lacidogna[1], Silvio Valente[1]

[1] Department of Structural Geotechnical and Building Engineering, Politecnico di Torino, Italy

[*] Corresponding author: alessandro.grazzini@polito.it

ABSTRACT

The delamination process of plasters applied for the repair work of historical walls was often caused by humidity phenomena or physical-mechanical cycles stress. In this paper a new experimental methodology has been conducted by testing in the laboratory mixed stone-mortar specimens and analyzing the delamination progression. The experiment simulated the recurring delamination in the stone walls of the Sacro Monte di Varallo, an UNESCO site in Piedmont (Italy). Through the monitoring by means of acoustic emission (AE) sensors during the tests it was possible to qualify the different fracture modes characterizing the delamination process, which takes place during the tests

at the interface between plaster mortar and stone block. AE is a non-destructive technique useful to estimate the amount of energy released from fracture propagation in the adherence surface between mortar and stone. The experimental results confirmed the stick-slip behaviour that characterises the friction process inside the delamination surface between repair mortar and masonry stone.

KEYWORDS: historical walls; repair plaster; acoustic emission; plaster delamination; laboratory test; fracture mode; stick-slip behavior.

1. INTRODUCTION

The detachment of the repair plasters applied to historical walls represents a serious problem of durability in the restoration work. The walls of historic buildings are often subject to degradation due to damp action from capillary rising or due to the action of freeze-thaw cycles [1, 2] (Fig. 1). These thermo-hygrometric cycles become mechanical stresses in the mortar-masonry interface, which intensity are often not compatible with mechanical strength of the materials leading to delamination. Many times the stresses are also caused by mechanical incompatibility between the plaster and the masonry layer. It can often happen that the application of repair mortars that are too rigid, when stressed by thermo-mechanical stress (~~freezing thawing~~ freeze-thaw cycles, environmental vibrations etc...) undergo a detachment due to the great difference in stiffness with respect to the masonry layer on which they had been applied [~~2, 3~~3-5]. The problem of detachment also occurs in conjunction with the application of new repair mortars for historical plasters, often with mechanical and thermo-hygrometric characteristics not similar to the diversified historical wall

Formatted: Highlight

supports and not durable compared to the thermo-hygro-mechanical stresses that the environment can induce (Fig. 2) [4-86-10].

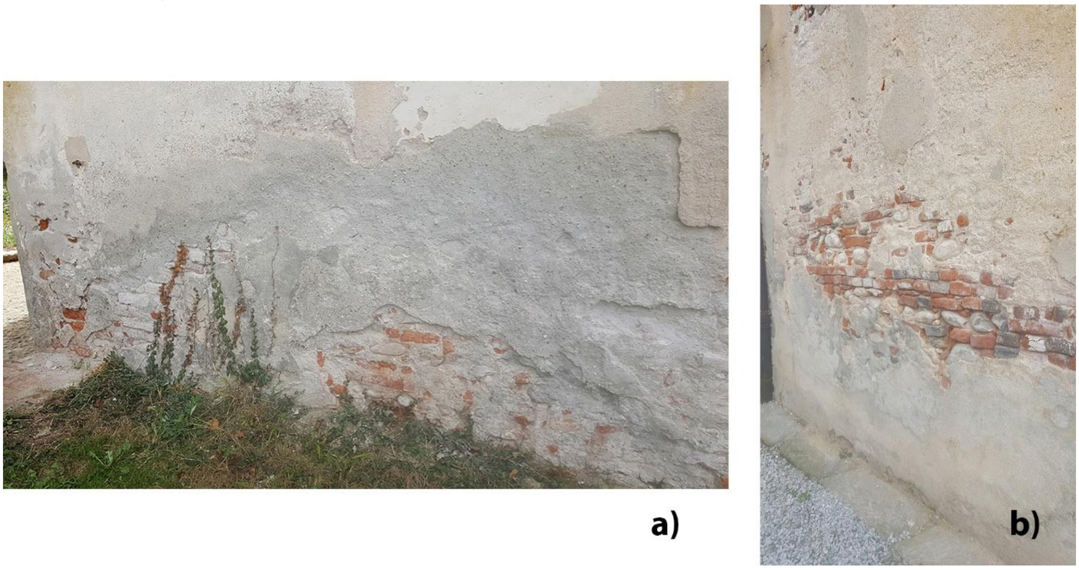


Fig. 1. Some examples of plaster detachment on historical walls due to: a) damp action from capillary rising, b) the action of ~~freezing-thawing~~ freeze-thaw~~n~~ cycles.

Formatted: Highlight
Formatted: Highlight
Formatted: Highlight

Fig. 2. Example of the mechanical incompatibility of patches made by cement mortar in a historical plaster based on lime mortar. The noticeable difference in stiffness of the concrete patch against the original lime-based plaster has favored the detachment under thermo-hygrometric stress.

Since the historical wall textures have very different physical and mechanical characteristics, in order for the restoration to offer a reasonable durability over time, it is essential to prepare preliminary tests for the pre-qualification of the restoration mortars to test their resistance to delamination phenomena when applied to a specific masonry support [79, 911-14]. This research concerns the description of a particular experimental testing methodology, performed in the laboratory on ad hoc specimens by coupling two layers of dehumidifying dehumifying repair mortar on a stone block, and tested to shear load. The specially created mortar laying discs favor the delamination process, whose strength also depends on the compatibility of the mechanical performances between the two contact surfaces. The experimentation was designed to provide a specific restoration site, that of the Sacro Monte di Varallo in Piedmont (Italy), with technical indications for the choice of the most compatible and durable mortars to be applied for the restoration of many decohesive plasters following particularly marked thermo-hygrometric cycles in the area. The Sacro Monte di Varallo is a UNESCO site featuring 45 chapels, built between the 15th and 18th centuries, which represent by stages the life of Christ (Fig 3). The chapels are built with stone masonry and their plasters, some also painted, highlight multiple detachments in large parts due to the abundance of rain and humidity that characterizes the mountain environment in which they are located (Fig. 3b) [1015].

Fig. 3. Same example of religious stone building at the Sacro Monte di Varallo: a) Nazaret building; b) Chapel of the Temptations.

Starting from what was performed in the previous experiments tests at the Politecnico di Torino Laboratory [7 109, 15], this research describes the results of a new experimental campaign performed on one new mixed specimen with improvements in the test setup. Monitoring of the detachment process due to delamination between repair mortar and stone block was performed using the Acoustic Emission (AE) technique. Through the monitoring of the acoustic energy released at the mortar-stone interface, the AE technique allowed to assess the delamination process and to identify the phases corresponding to the different fracture modes [11 1416-19].

In this research the study of the stick-slip behavior that characterizes the experimental course of the test has been deepened. Stick–slip is a well-known example of a friction oscillation produced at a sliding interface, which often triggers friction induced vibrations and accelerates surface [~~15~~20]. The phenomenon is similar to what characterizes the structural behavior of dry stone walls, whose in-plane mechanical strength ~~in the plane~~ is precisely characterized by friction and mutual meshing between the stones [~~16~~21]. The AE monitoring took all the stick-slip stages where a release of energy occurs at the interface between the two coupled materials. The process of detachment and delamination does not occur in a single phase, but in several phases characterized by falls and subsequent resumption of loading, since the path of resistance is longer by exercising on the entire length of the two symmetrical contact surfaces between the two materials of the mixed-specimen.

Formatted: Highlight

2. EXPERIMENTAL SETUP

The tests in the laboratory involved one new mixed specimen produced ad hoc following a test methodology already tested in previous experiments aimed at assessing the compatibility and mechanical durability of strengthening mortar and masonry support [~~1,~~ 3]. The specimen was composed by assembling a block of gneiss stone, a granitic metamorphic rock with ~~similar~~ mechanical characteristics similar to those that make up the wall texture of the chapels of the Sacro Monte di Varallo, with two layers of dehumidifying plaster mortar applied to the narrower side faces of the stone block (Fig. 4). To facilitate the adhesion of the repair mortar, the stone surface of the block was treated with a special staking performed with a pneumatic hammer, in order to make it more wrinkled in analogy with the real one. The repair mortar used is a pre-mixed transpirant product~~,~~ made from natural hydraulic lime and Natural-Pozzolan, indicated for the dehumidifying restoration of the plaster to be applied on historical walls. Young's modulus of this repair mortar was 7000 ~~MPa~~ MPa, the compressive strength, evaluated according to UNI 6556 technical code, was 33.8 ~~Mpa~~ MPa.

Formatted: Highlight

Formatted: Highlight

Formatted: Highlight

Formatted: Highlight

Formatted: Highlight

Formatted: Highlight

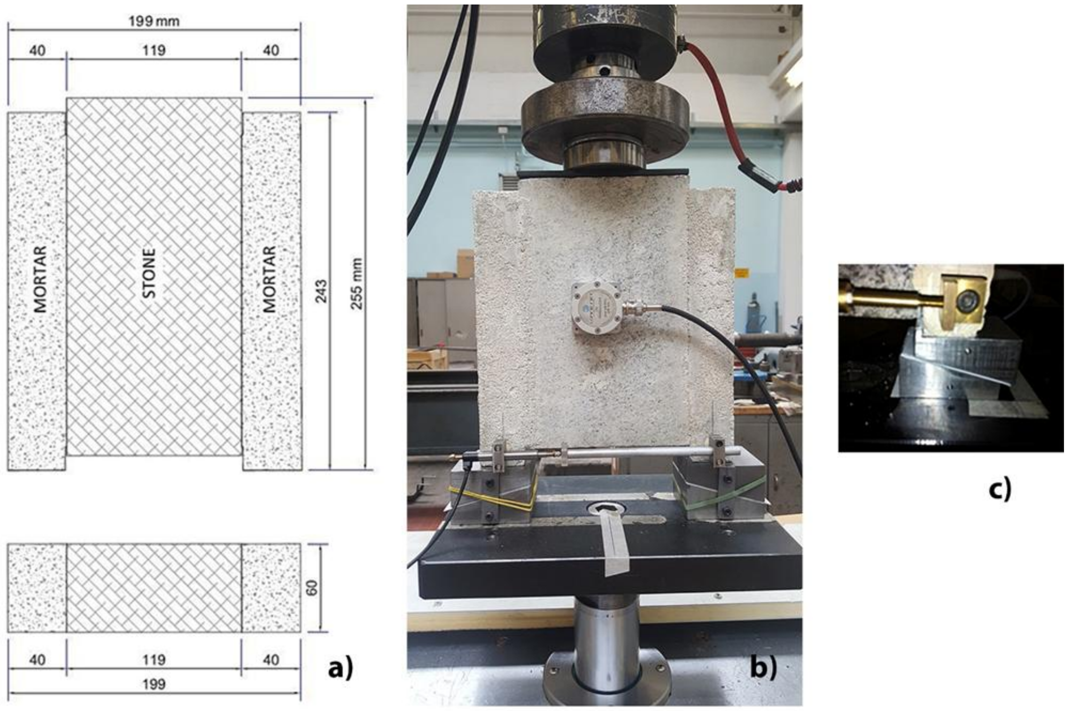


Fig. 4. Geometry of composite specimen (a); test setup (b); wedges' geometry (c)

The two layers of plaster have been applied with a vertical asymmetry with respect to the lateral surface of the stone block (Fig. 4a-b), creating notches that trigger the detachment process and assess the adherence capacity of each dehumidified mortar applied to a specific masonry wall. The specimens were instrumented with an inductive horizontal displacement transducer, as shown in Fig. 4b. The vertical displacements were recorded by the piston's stroke of the test machine. The shear tests were carried out through monotonous compression load performed with the aid of a 100 kN servo controlled machine (MTS, USA), by controlling the horizontal ~~opening~~ displacement with a speed opening at 0.0001 mm/s. The mortar layers rested on a double system of steel wedges, as showed in Fig. 4. The steel wedges were coupled by a Teflon layer thick 1 mm in order to for reduce the horizontal friction. The specimens were labeled with "SM" (stone block-mortar), followed by a number indicating the order [~~1, 2~~16-19].

3. ACOUSTIC EMISSION MONITORING

The estimation of the fracturing process and the classification of active cracks is an important tool offered by AE technique, and more in general by Non-destructive Monitoring Techniques [~~17~~22]. In this work, AE signals generated by micro-cracks during the damaging process are detected by AE sensors attached on the specimen's surface by means of a silicon glue. The signal waveforms are recorded by a dedicated AE detecting system. In laboratory tests, the authors exploited a leading-edge monitoring equipment [~~18-20~~23-25] for multichannel data processing, and consisting in synchronized units for Acoustic Emission monitoring provided by LEANE Ltd (Italy). Each of these units analyzes in real time, and transmits to a computer, all the characteristic parameters of an

Formatted: Highlight

Formatted: Highlight

Formatted: Highlight

ultrasonic event. Specific waveform parameters are set as in the following: Peak Definition Time (PDT) = 50 μs; Hit Definition Time (HDT) = 150 μs; Hit Lockout Time (HLT) = 300 μs. In this manner, each AE event is identified by a progressive number and characterized by a series of data giving the amplitude and time duration of the signals and the number of oscillations. Moreover, the absolute acquisition time and signal frequency are also given, so that, through an analysis of signal frequency and time of arrival, it is possible to identify the group of signals belonging to the same AE event and to localize it. Each unit is equipped with a pre-amplified wide-band piezoelectric sensor, which is sensitive in a frequency range between 50 kHz and 800 kHz. The signals acquisition threshold can be set in a range between 100 μV and 6.4 mV~~.~~, in order to avoid environmental noise. The AE waves are amplified with 60 dB gain before they have been processed, setting the acquisition threshold level up to 2 mV.

4. EXPERIMENTAL RESULTS AND DISCUSSION

In order to classify active cracks, the AE signals parameters, such as rise time and peak amplitude, are considered: in this way, the rise angle (RA) value can be calculated. RA is defined as the ratio of the rise time (expressed in ms) to the peak amplitude (expressed in V). The shape of the AE waveforms is typical of the fracture mode. Shear events are characterized by long rise times and usually high amplitudes, whereas low rise time values are typical of tensile crack propagations. These conditions can be represented in the RA value analysis [~~17~~22, 26]. Moreover, another parameter used to characterize the cracking mode is the Average Frequency (AF) expressed in kHz. In general, the shift from higher to lower values of AF could indicate the shift of the cracking mode from tensile to shear [~~17~~22, 27]. Nevertheless, when a cracking process involves the opening of large cracks (Mode I), the frequency attenuation must be a function of this discontinuity. In other words, in this case the wavelength of the AE signals needs to be larger for the crack opening to be overcome, and the shift of the frequencies from higher to lower values could support also a dominant tensile cracking mode.

In the following, the results of the AE monitoring are described for specimen SM4. This test constitutes a further refinement of the type of test compared to those already performed and whose results have been described in previous publications [~~12-14~~17-19]. The results of the SM4 sample are in line with what was found in the analogous tests previously performed. The load vs. time diagram of the specimen SM4, together with AE cumulated curve, is shown in Figure 5a. During the first part of the test, when the load increases proportionally over time, there are few AE signals. However, a clear growth in the AE hits is obtained in the correspondence of each sharply decrease of the loading process. This supports the fact that the AE signals are mainly associated with the energy emitted by the specimen during the delamination of the mortar from the stone block, which can be associated with snap-back instabilities [~~19~~24,~~ 21~~28] in a stick-slip process [~~15~~20]. All the AE signals detected, about 180 hits, are represented in Figure 5a. However, most of these hits are characterized by a random oscillatory appearance, which results from the overlapping of multiple burst type signals of undistinguished amplitudes. This is due to the very brittle behavior of the above mentioned stick-slip process, which generated many signals overlaps. On the other hand, all the AE signals obtained during the test, proving a clear dominating average frequency, and a sharp peak in the voltage are shown in Figure 5b,c and used to find AF and RA values. The dominating frequency has been calculated by using the FFT (Fast Fourier Transform).~~ The Fourier Transform is a linear transform that takes AE signals from time domain and returns them into frequency domain.~~

Formatted: Highlight

In other words, it commutes a complex function into another complex function, providing useful information about the change in domain. For AE signals, this change in domain turns out the AE dominating frequency, that is the signal frequency having the highest spectrum. Moreover, using the ordinary least squares method, the linear regressions of the signal frequencies (AF) and rise angles (RA) are traced during the whole test [29, 30], as showed in Figure 5b,c. Considerable variations from the mean trend were observed in particular immediately after 100 seconds from the beginning of the test, around 200 seconds, and around 420 seconds towards the end of the test. In the first phase, from 0 to 120 seconds, rise angles with low values prevail, while the frequencies are oscillating with the higher values more distant from the average trend. This indicates a prevalent Mode I in the delamination process in the initial loading phase. In the second phase, the highest values of the RAs during the whole test were obtained, while the frequencies continue to oscillate with the lowest values more distant from the average. This behavior shows how the delamination process that leads to collapse develops within a stick-slip process involving sudden stress drops, and it is mainly accompanied by the sliding of the mortar with respect to the stone block (Mode II). In the final phase, over 400 seconds, the frequencies are still lowered below the average line, while the RAs once again become low, so it can be said that there is no prevailing fracture mode before the specimen collapses definitively.

Formatted: English (United States)

Formatted: Highlight

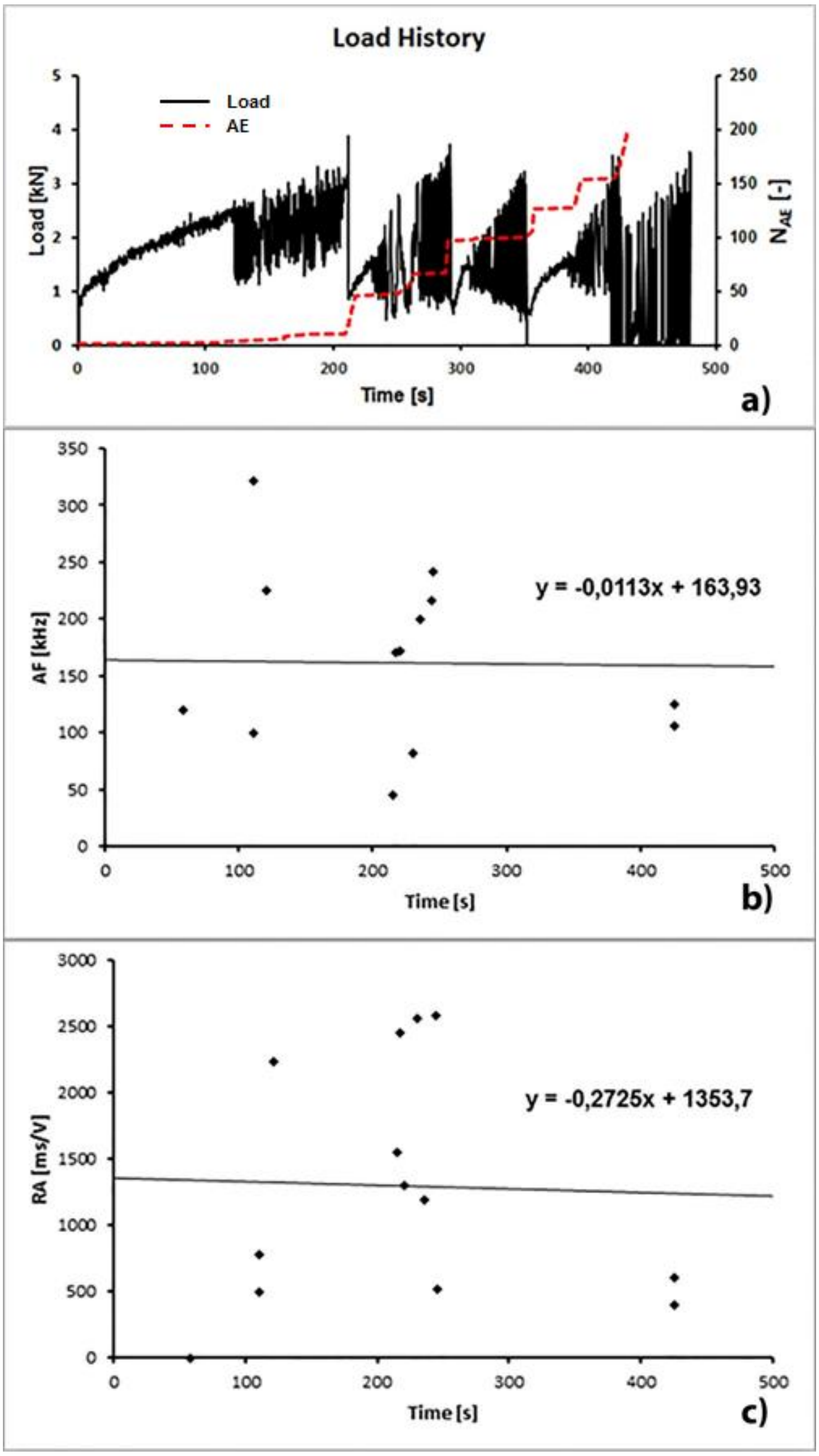


Fig. 5. Load and Cumulated AE (a); Average Frequency, AF (b); and Rise Angle, RA (c).

Formatted: Highlight

5. CONCLUSIONS

The problem of the delamination of dehumidifying plasters applied on historical walls was experimentally analyzed by means a shear test on a mixed stone-plaster sample. The test is useful for assessing the compatibility of new repair mortars against the historic masonry support, to whose interface often stresses arise due to the excessive rigidity of the repair mortars when they are stressed by thermal or mechanical cycles. The innovative experimental procedure consists of a static test in which shear stresses are exerted at the interface between mortar and stone, in order to simulate the stresses that can be generated cyclically during the useful life of the interaction between the two materials.

The test was also monitored with the acoustic emission (AE) technique which allowed to identify the fracture mode at the interface between stone and repair mortar. Through the analysis of the Average Frequency it was possible to identify a first phase of the test in which a fracture of mode I for traction prevails, followed by a second phase of mode II for shear load during the delamination process. The ~~analisys~~analysis of acoustic emission signals have confirmed the stick-slip behavior that characterizes the debonding process.

6. REFERENCES

[1] M. Collepardi, Degradation and restoration of masonry walls of historical buildings, Mat. and Struct. 23 (1990) 81–102.

[2] D. Gulotta, C. Tedeschi, L. Binda, L. Toniolo. Durability of porous material to salt decay (review), in: Proceedings of the 11th International Congress on Deterioration and Conservation of Stone, Torun, Poland, 2008.

[~~2~~3] P. Bocca, A. Grazzini, Mechanical properties and freezing-thawing durability of strengthening mortars, J. Mat. Civ. Eng. 25 (2013) 274-280. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000597.

[~~3~~4] A. Török, B. Szemerey-Kiss, Freeze-thaw durability of repair mortars and porous limestone: compatibility issues, Progr. Earth Planet. Sci. 6 (2019), ~~-~~ doi:10.1186/s40645-019-0282-1.

[5] I. Papayianni, J. Hughes. Testing properties governing the durability of lime-based repair mortars, Rilem Tech. Lett. 3 (2018), doi: 10.21809/rilemtechlett.2018.81.

[~~4~~6] A. Grazzini, In Situ Analysis of Plaster Detachment by Impact Tests, App. Sci. 9 258 (2019) 1-11. https://doi.org/10.3390/app9020258.

[~~5~~7] P. Bocca, A. Grazzini, D. Masera, Fatigue behaviour analysis for the durability prequalification of strengthening mortars, J. Phys.: Conf. Ser. 305 (2011). doi:10.1088/1742-6596/305/1/012041.

[~~6~~8] M.R. Valluzzi, L. Binda, C. Modena, Experimental and analytical studies for the choice of repair techniques applied to historic buildings, Mat. and Struct. 35 (2002) 285-292.

[~~7~~9] P. Bocca, A. Grazzini, Experimental procedure for the pre-qualification of strengthening mortars, Int. J. of Arch. Heritage 6 (2012) 302-321. https://doi.org/10.1080/15583058.2010.534232.

Formatted: English (United States)

Formatted: English (United Kingdom)

Formatted: Superscript

Formatted: English (United Kingdom)

Field Code Changed

Formatted: English (United States)

Field Code Changed

Field Code Changed

[~~8~~10] V. Fassina, M. Favaro, A. Naccari, M. Pigo, Evaluation of compatibility and durability of a hydraulic lime-based plaster applied on brick wall masonry of historical buildings affected by rising damp phenomena, J. of Cultural Her. 3 (2002) 45–51.

[~~9~~11] P. Bocca, A. Grazzini, D. Masera, A. Alberto, S. Valente, Mechanical interaction between historical brick and repair mortar: Experimental and numerical tests, J. Phys.: Conf. Ser. 305 (2011). doi: 10.1088/1742-6596/305/1/012126.

[12] J. Madera, J. Kruis, T. Koudelka, R. Sovjak. Analysis of plaster detachment and experimental determination of plaster–masonry interface shear capacity, AIP Conf. Proc. 2116 (2019). doi: 10.1063/1.5114060.

[13] D. Gulotta, L. Toniolo, L. Binda, C. Tedeschi, R.P.J. Van Hees, T. Nijland. Investigation of commercial ready-mixed mortars for architectural heritage, in: Structural Studies, Repairs and Maintenance of Heritage Architecture XI, WIT Press, Southampton, UK, 2014, 231-241, doi: 10.2495/STR090211.

[14] C. Blaeuer, B. Rousset, Testing the mechanical and the petrophysical behaviour of repair mortars, in: Proceedings of the 11th International Congress on Deterioration and Conservation of Stone, Torun, Poland, 2008.

[~~10~~15] A. Carpinteri, Il patrimonio pittorico murale dei Sacri Monti. Monitoraggio, valorizzazione e recupero, Aracne ed., Ariccia, Italy, 2017.

[~~11~~16] P. Bocca, S. Valente, A. Grazzini, A. Alberto, Detachment analysis of dehumidified repair mortars applied to historical masonry walls, Int. J. of Arch. Heritage 8 (2014) 336-348. https://doi.org/10.1080/15583058.2013.826304.

[~~12~~17] A. Grazzini, G. Lacidogna, S. Valente, F. Accornero, Delamination of plasters applied to historical masonry walls: analysis by acoustic emission technique and numerical model, IOP Conf. Series: Mat. Scie. and Eng. 372 (2018) 1-7. DOI: 10.1088/1757-899X/372/1/012022.

[~~13~~18] A. Grazzini, G. Lacidogna, S. Valente, F. Accornero, Detachment monitoring of repair mortar applied to historical masonry stone by acoustic emission technique, in: Proceedings of the 11th International Conference on Structural Analysis of Historical Constructions (SAHC), Cusco, Perù, 2018. DOI: 10.1007/978-3-319-99441-3_236.

[~~14~~19] A. Grazzini, G. Lacidogna, S. Valente, F. Accornero, Detachment of plasters in masonry buildings: analysis by acoustic emission and numerical simulation, in: Proceedings of the 18th International Conference on Experimental Mechanics (ICEM), Bruxelles, Belgium, 2018. https://doi.org/10.3390/ICEM18-05431.

[~~15~~20] J.S. Park, S.M. Lee, B.S. Joo, H. Jang, The effect of material properties on the stick–slip behavior of polymers: A case study with PMMA, PC, PTFE, and PVC, Wear 378-379 (2017) 11-16. http://dx.doi.org/10.1016/j.wear.2017.01.097.

[~~16~~21] A. Grazzini, M. Zerbinatti, Static and seismic behaviour of different dry stone wall textures, in: Proceedings of the 10th International Masonry Conference, Milan, Italy, 2018.

Formatted: Italian (Italy)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Field Code Changed

Field Code Changed

Field Code Changed

[~~17~~22] A. Carpinteri, G. Lacidogna, F. Accornero, A. Mpalaskas, T. Matikas, D. Aggelis, Influence of damage in the Acoustic Emission parameters, Cement and Concrete Composites, 2013, 44:9-16. http://dx.doi.org/10.1016/j.cemconcomp.2013.08.001

Field Code Changed

[~~18~~23] A. Carpinteri, G. Lacidogna, F. Accornero, Fluctuations of 1/f noise in damaging structures analyzed by Acoustic Emission, Applied Sciences, 2018, 8:1685. http://dx.doi.org/10.3390/app8091685

Field Code Changed

[~~19~~24] G. Lacidogna, F. Accornero, A. Carpinteri, "Influence of snap-back instabilities on Acoustic Emission damage monitoring", Engineering Fracture Mechanics, 2019, 210:3-12. DOI: 10.1016/j.engfracmech.2018.06.042

[~~20~~25] G. Lacidogna, F. Accornero, M. Corrado, A. Carpinteri, Crushing and fracture energies in concrete specimens monitored by Acoustic Emission, in: Proceedings of the 8th International Conference on Fracture Mechanics of Concrete and Concrete Structures, FraMCoS 2013, Toledo, Spain, 2013.

[26] D.G.Aggelis, E.Z.Kordatos, T.E.Matikas, Acoustic emission for fatigue damage characterization in metal plates, Mechanics Research Communications, 38 (2011), 106-110.

[27] D.G.Aggelis, D.V.Soulioti, N.Sapouridis, N.M.Barkoula, A.S.Paipetis, T.E.Matikas, Acoustic emission characterization of the fracture process in fibre reinforced concrete, Construction and Building Materials, 25 (2011), 4126-4131.

[~~23~~28] A. Carpinteri, F. Accornero, Multiple snap-back instabilities in progressive microcracking coalescence, Eng. Fract. Mech. 187 (2018), 272-281.

[29] G. Livitsanos, N. Shetty, E. Verstrynge, M. Wevers, D. Van Hemelrijck, D.G. Aggelis, Shear failure characterization in masonry components made with different mortars based on combined NDT methods, Construction and Building Materials 220, (2019) 690-700.

[30] E. Tsangouri, O. Remy, F. Boulpaep, S. Verbruggen, G. Livitsanos, D.G. Aggelis, Structural health assessment of prefabricated concrete elements using Acoustic Emission: Towards an optimized damage sensing tool, Construction and Building Materials, 206 (2019) 261-269.

Figure 1
Click here to download high resolution image

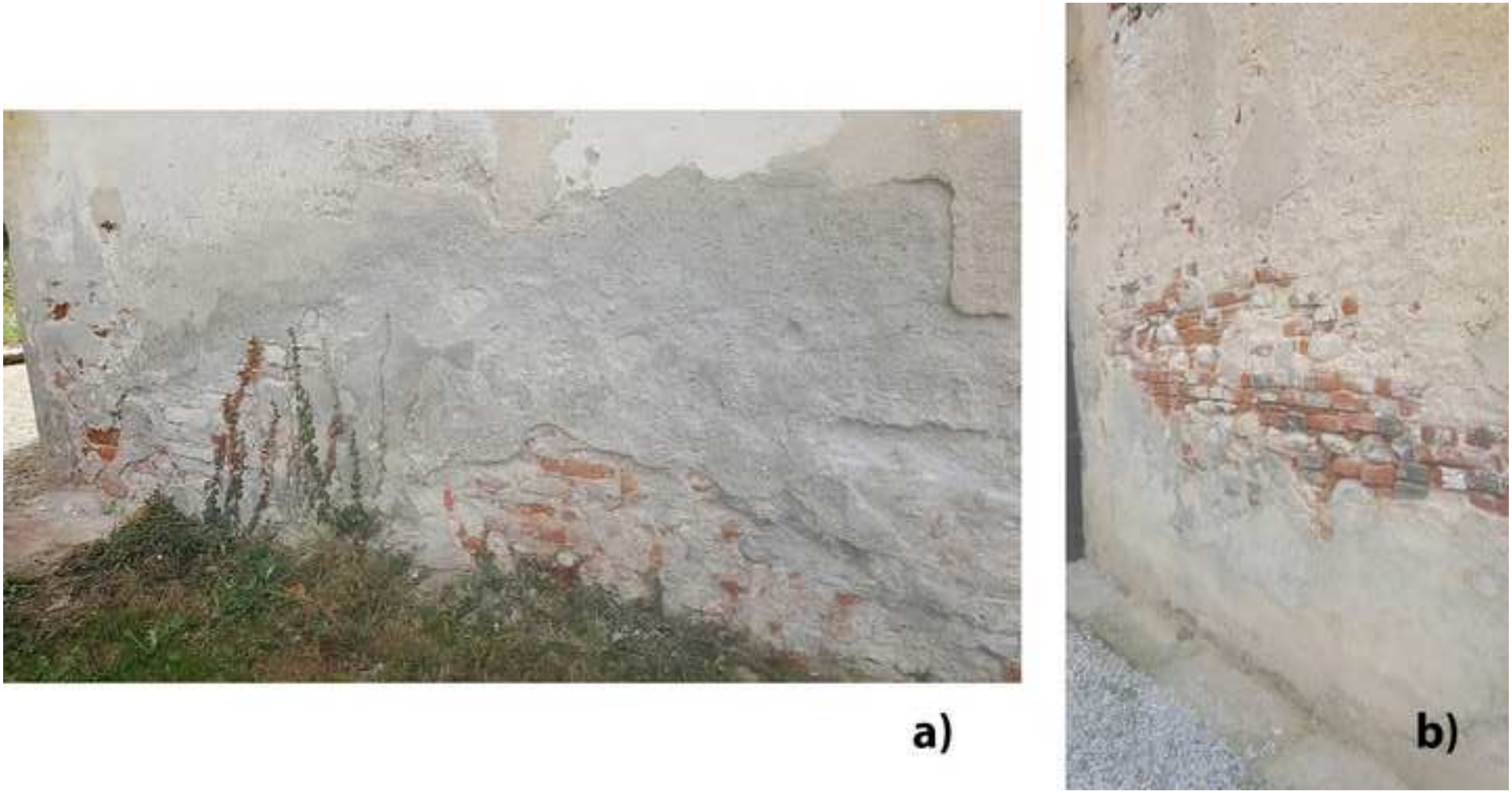


Figure 2
Click here to download high resolution image

Figure 3
Click here to download high resolution image

Figure 4
Click here to download high resolution image

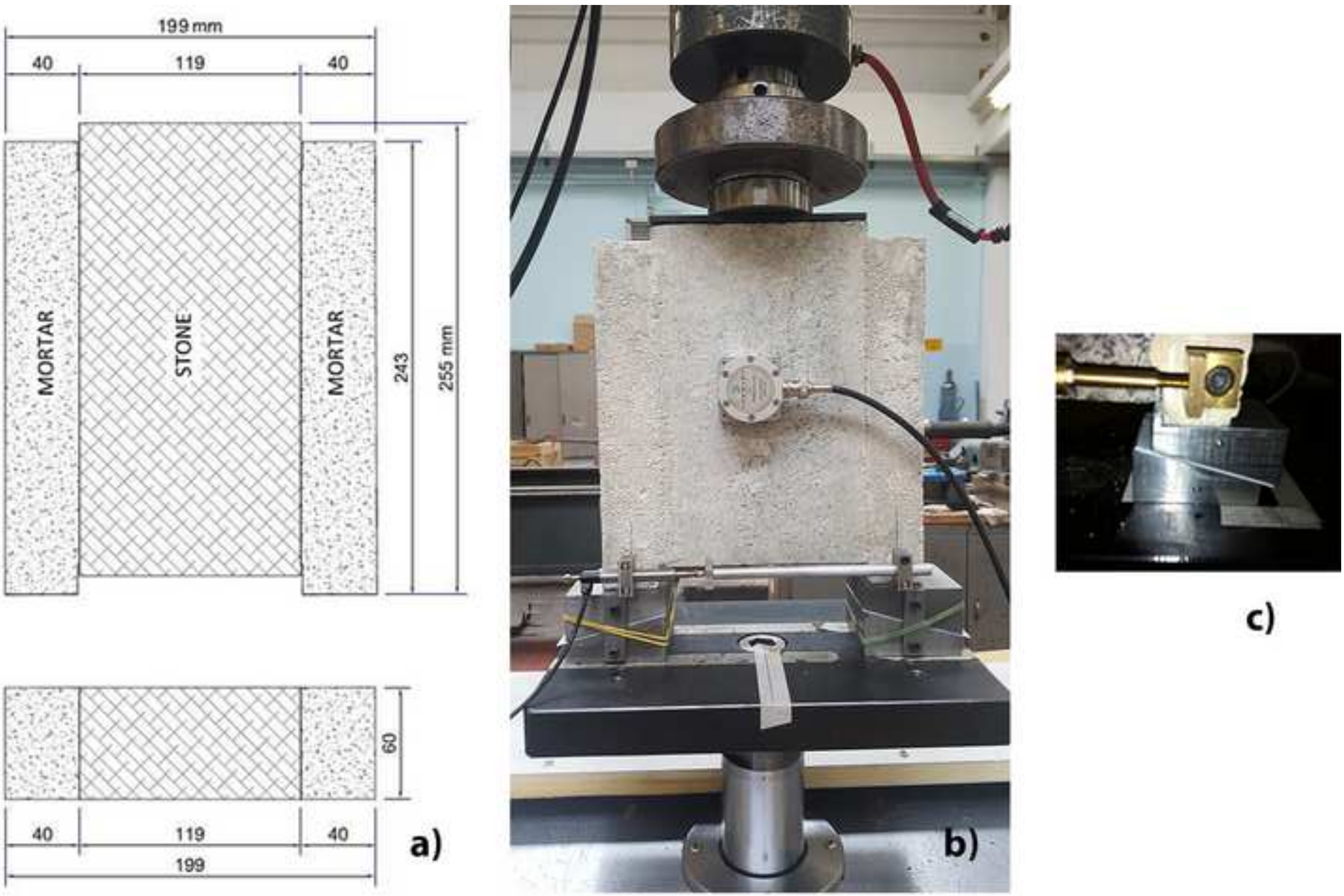
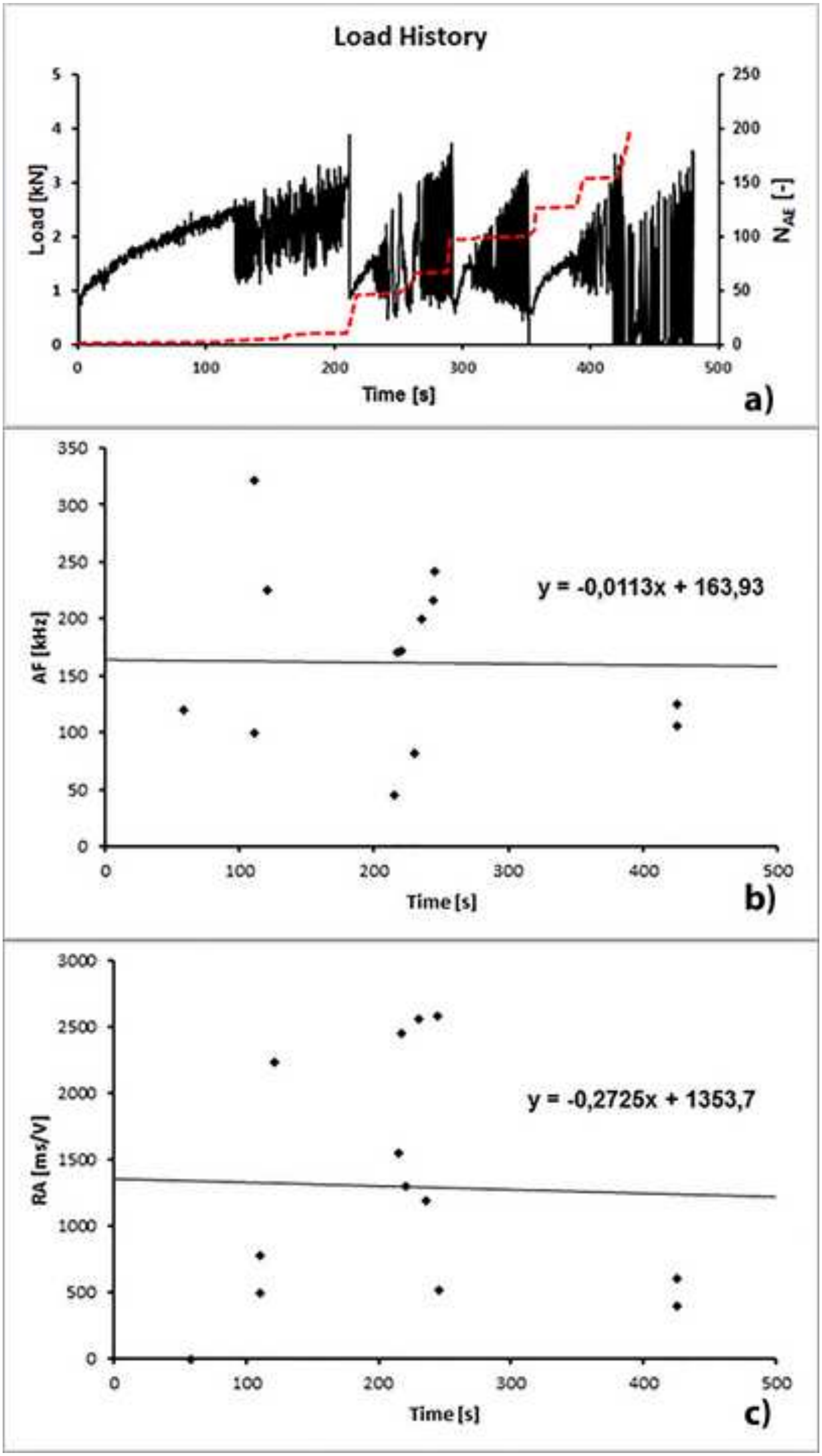


Figure 5

Click here to download high resolution image



REPLY TO EDITOR'S AND REVIEWERS' COMMENTS

Journal: Construction & Building Materials

Manuscript Number: CONBUILDMAT_S_19_09703

Title: Acoustic emission and numerical analysis of the delamination process in repair plasters applied to historical walls

Authors: Alessandro Grazzini, Federico Accornero, Giuseppe Lacidogna, Silvio Valente

The authors thank the Editor and the Reviewer for their useful suggestions, which were very useful in preparing an improved version of the manuscript.

Concerning the list of comments, detailed answers are provided below.

All the changes requested are highlighted with a yellow background in the improved manuscript.

Reviewer 2

Archaeometric research is always very important to the preservation of historical culture of mankind. This enjoyable paper refers to very important aspect of monument restoration with mortars and the consequent issues arising from materials mismatch and the influence of environmental degradation of the materials' interfaces studied with the AE technique.

The authors are grateful to the Reviewer for the positive comments to their manuscript.

I only have some minor suggestions with respect to the content and results presentation.

Minor comments and phrasal corrections:

1. Possibly in page 3 of manuscript the expression "freezing-thawing cycles" can be better rephrased to "freeze-thaw cycles" and also in Fig.1 legend.

We accepted the Reviewer suggestion. The manuscript has been edited accordingly:

«[…] It can often happen that the application of repair mortars that are too rigid, when stressed by thermo-mechanical stress (freeze-thaw cycles, environmental vibrations etc...) undergo a detachment due to the great difference in stiffness with respect to the masonry layer on which they had been applied [2, 3].»

«Fig. 1. Some examples of plaster detachment on historical walls due to: a) damp action from capillary rising, b) the action of freeze-thaw cycles.»

2. The expression in page 6 top ".....whose mechanical strength in the plane..." can be possibly rephrased to : "...whose in-plane mechanical strength......"

We accepted the Reviewer suggestion. The manuscript has been edited accordingly:

«[…] whose in-plane mechanical strength is precisely characterized by friction and mutual meshing between the stones [16]»

3. Page 6 bottom "MPa" instead of Mpa.

We accepted the Reviewer suggestion. The manuscript has been edited accordingly.

4. Can the authors be a bit more specific on the composition or the commercial origin of the restoration mortar product refered to in page 6, experimental section ? Also, the nature of the stone (e.g. marble, or asbestolithic etc) would be nice to be mentioned too.

We accepted the Reviewer suggestion. The manuscript has been edited accordingly:

«[…] The specimen was composed by assembling a block of gneiss stone, a granitic metamorphic rock with mechanical characteristics similar to those that make up the wall texture of the chapels of the Sacro Monte di Varallo, with two layers of dehumidifying plaster mortar applied to the narrower side faces of the stone block […]»

«[…] The repair mortar used is a pre-mixed transpirant product, made from natural hydraulic lime and Natural-Pozzolan, indicated for the dehumidifying restoration of the plaster to be applied on historical walls. […]»

5. Some more information on the compression experiment speed in mm/min and machine type could be helpful.

The static compressive tests were performed with the aid of a 100 kN servo controlled machine (MTS, USA). Monotonous compression tests were carried out by controlling the horizontal opening with a speed opening at 0.0001 mm/s.

Also, the type of the AE-equipment if it is a commercial system.

By considering the Reviewer's suggestion, the following remarks have been added in the revised manuscript:

<< In laboratory tests, the authors exploited a leading-edge monitoring equipment [18-20] for multichannel data processing, and consisting in synchronized units for Acoustic Emission monitoring provided by LEANE Ltd, Italy. Each of these units analyzes in real time…>>

6. In Figure 5a, please indicate the red dashed line is cumulated AE though obvious.

We accepted the Reviewer suggestion. The manuscript has been edited accordingly.

7. Though the authors follow a well-established path for analyzing AE-average frequency (Fig. 5b) and AE-Rise Angle (Fig. 5c) is seems that the data which is very analytically shown, do not obey the linear functions shown in both graphs. To me the results can be grouped in three major phases:

a. 0- 220 sec : Principal Cracking (MODE II NOT MODE I AS MODE I MUST BE JUSTIFIED AND MODE II IS NATURAL SINCE ITS A SHEAR TEST !)

b. 200-350 sec: Stic - Slip Mechanism as shown in 5a *c. ca. 420 s: Total failure by crack propagation.*

Again, if mode I cracks are present due to poisson effect then they should be also visible on the failure surfaces.

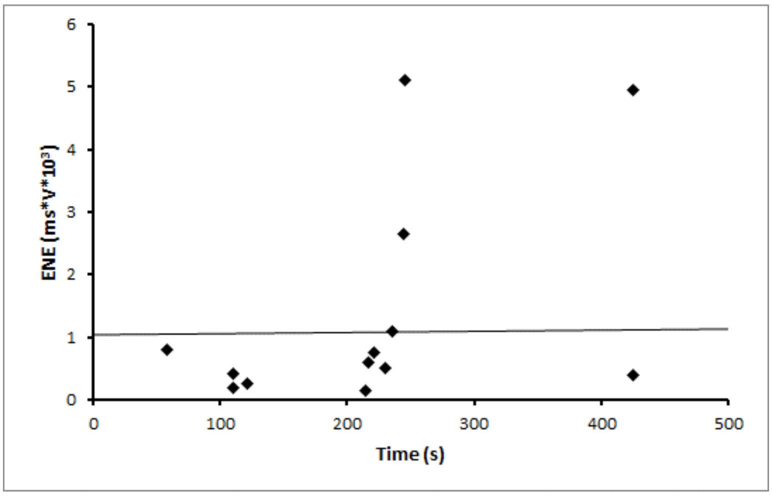
Phases a and b, do show similar frequencies and rise time angles because they are related to mode II cracking (initial and stic-slip propagation.)

Considering phases “b” and “c”, the authors totally agree with the Reviewer, as reported in the original manuscript.

Concerning phase “a”, although it may seem peculiar for a shear test, some evidences of initial Mode I cracking stage are detected. As a matter of fact, << … from 0 to 120 seconds, rise angles with low values prevail, while the frequencies are oscillating with the higher values more distant from the average trend. This indicates a prevalent Mode I in the delamination process in the initial loading phase. >> As suggested by the Reviewer, Mode I is justified both by AE testing and by the specimen behavior: as the wedges geometry (Fig. 4c) allows the initial sliding of the composite, a crack opening (Mode I) is manifest during the first loading stage.

8. What about the Amplitude - Energy vs time plots ? do they deliver any better views?

Energy vs Time diagram leads to the same conclusions as reported in the manuscript. For the sake of completeness, the abovementioned diagram is reported in the following:



Reviewer 3

The paper is devoted to interesting problem: the investigation of delamination process of plasters applied for the repair work of historical walls. The problem has both high scientific interest and cosial effect. The author used modern experimental technique and data treatment algorithm to investigate the fracture process of stone walls. The paper is good example of application of AE technique. The results of the paper could be interesting both for real practical application and for future laboratory studies which include cluster analysis of AE signals.

The paper reports few tests only and the test include few number of AE signals. But it is naturally for full size test.

The paper is clear and i have no significant comments to improve the paper.

The authors are grateful to the Reviewer for the positive comments to their manuscript.

Reviewer 4

I would like to address some comments and questions to the authors:

** Section 2. In the text: "Specific waveform parameters are set as in the following: Peak Definition Time (PDT) = 50 <mu>s; Hit Definition Time (HDT) = 150 <mu>s; Hit Lockout Time (HLT) = 300 <mu>s". Could you please explain how did you adjusted these parameters? Could you please explain the process of selection of PDT, HDT and HLP to guarantee adequate hit and hit parameters obtention?*

The Peak Definition Time (PDT), the Hit Definition Time (HDT), and the Hit Lockout Time (HLT), are not adjusted basing on specific materials. The PDT/HDT/HLT settings are related to the distance between the supposed damage sources and the sensors: they depend on the size of the tested specimen or structure. Basically, the selection process of the PDT/HDT/HLT settings is based to past experimental campaigns conducted by the Authors, involving specimens of the same size featured by the samples tested in the present work.

** Section 3. In the text: "The signals acquisition threshold can be set in a range between 100 <mu>V and 6.4 mV". Could you please explain the reasons of selecting those Thresholds?*

By considering the Reviewer's suggestion, the following remarks have been added in the revised manuscript:

<< The signals acquisition threshold can be set in a range between 100 μV and 6.4 mV, in order to avoid environmental noise. >>

** Section 4. Both, the experimental program and the analyses of mode I and Mode II are very interesting. Could you please include some more details on the test setup?*

The complete description of the test setup is given in paragraph 2 (Experimental setup).

Could you please include some other references related to the application of RA and AF to analyze the cracking process?.

We accepted the Reviewer suggestion. The manuscript has been edited accordingly.

** Section 4. "In the text: On the other hand, all the AE signals obtained during the test, proving a clear dominating average frequency, and a sharp peak in the voltage are shown in Figure 5b,c and used to find AF and RA values. The dominating frequency has been calculated by using the FFT (Fast Fourier Transform).". Could you include more explanations and details on the application and results obtained in of FFT analyses?*

As briefly reported in the manuscript, the dominating frequency has been calculated by using the FFT (Fast Fourier Transform). The Fourier Transform is a linear transform that takes AE signals from time domain and returns them into frequency domain. In other words, it commutes a complex function into another complex function, providing useful information about the change in domain. For AE signals, this change in domain turns out the AE dominating frequency that is the signal frequency having the highest spectrum.

** Section 4 .In the text: "On the other hand, all the AE signals obtained during the test, proving a clear dominating average frequency, and a sharp peak in the voltage are shown in Figure 5b,c and used to find AF and RA values. The dominating frequency has been calculated by using the FFT (Fast Fourier Transform)". Could you please include a brief explanation of the results obtained for you with FFT?*

Please refer to the previous answer.

** Section 4, last paragraph and Figure 5. I think this paragraph is very important, but sincerely I could not see very well the trends shown in Figures 5b and c. Could you please include additional explanations on the trends you observed for AF and RA? There is dispersion in data shown in RA and AF. Could you please refer to that in the text of the manuscript?*

As reported in the manuscript, the linear regressions of the signal frequencies and rise angles are traced during the whole test, observing their mean trends. The authors would like to point out how the mean trend is used to highlight the large RA and AF variations, fixing the three phases of the damaging process:

<< In the first phase, from 0 to 120 seconds, rise angles with low values prevail, while the frequencies are oscillating with the higher values more distant from the average trend. This indicates a prevalent Mode I in the delamination process in the initial loading phase. In the second phase, the highest values of the RAs during the whole test were obtained, while the frequencies continue to oscillate with the lowest values more distant from the average. This behavior shows how the delamination process that leads to collapse develops within a stick-slip process involving sudden stress drops, and it is mainly accompanied by the sliding of the mortar with respect to the stone block (Mode II). In the final phase, over 400 seconds, the frequencies are still lowered below the average line, while the RAs once again become low, so it can be said that there is no prevailing fracture mode before the specimen collapses definitively. >>

ACOUSTIC EMISSION AND NUMERICAL ANALYSIS OF THE DELAMINATION PROCESS IN REPAIR PLASTERS APPLIED TO HISTORICAL WALLS

Alessandro Grazzini, Federico Accornero, Giuseppe Lacidogna, Silvio Valente

Politecnico di Torino (Italy)

HIGHLIGHTS

- **-** The delamination process recurring between plaster and stone walls of the UNESCO site "Sacro Monte di Varallo" in Italy has been simulated by new laboratory tests.
- - From the tests has been established as the delamination process between repair mortar and masonry stones is characterized by a stick-slip behaviour.
- - The Acoustic Emission (AE) technique monitoring describes the fracture modes characterizing the delamination at the interface between the plaster mortar and the stone blocks.

***Declaration of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

***Author Contributions Section**

ACOUSTIC EMISSION AND NUMERICAL ANALYSIS OF THE DELAMINATION PROCESS IN REPAIR PLASTERS APPLIED TO HISTORICAL WALLS

Alessandro Grazzini, Federico Accornero, Giuseppe Lacidogna, Silvio Valente

Politecnico di Torino (Italy)

Author Contribution Statement

Alessandro Grazzini: Conceptualization, Resources, Writing, Visualization

Federico Accornero: Formal Analysis, Data Elaboration, Writing

Giuseppe Lacidogna: Metodology, Supervision, Validation, Review & Editing

Silvio Valente: Software, Investigation