ACOUSTIC EMISSION MONITORING OF FRESCOS DEGRADATION IN A XVII\textsuperscript{th} CENTURY CHAPEL OF THE “SACRED MOUNTAIN OF VARALLO” (ITALY)

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ABSTRACT

The present paper describes the results of the Acoustic Emission monitoring, performed for five months in order to assess the structural behaviour and the frescos degradation of a XVII\textsuperscript{th} Century Chapel belonging to the Sacred Mountain of Varallo (Italy). The Sacred Mountain of Varallo is composed of 45 Chapels, some of which are isolated, while others are part of monumental groups, containing over 800 life-size wooden and multicoloured terracotta statues, which represent the Life, the Passion and the Death of Christ. The site is considered the most notable example in the group of Sacred Mountains of Piedmonts, a complex that has been included in the UNESCO World Heritage List since 2003.

The Chapel number 17, dedicated to the Mount Tabor episode of Christ Transfiguration, shows some structural concern due to an existing large crack and some degradation of the high valuable frescos, which tend to detach from the masonry support.

In order to assess the evolution of the phenomena, an Acoustic Emission monitoring apparatus was used, with six sensors that enable the recording of the signals and localization of the events. In addition, a detailed survey of the Chapel was provided, together with a structural finite element simulation.

The results of the monitoring show that the large crack is stable, while the process of detachment of the frescos is evolving cyclically. It seems that the frescos degradation could be mainly related to the diffusion of moisture in the mortar substrate. Some preliminary laboratory tests also confirm that Acoustic Emissions are recorded in mortar samples subjected to moisture diffusion.

Keywords: Acoustic emission monitoring, Structural assessment, Frescos detachment

1. INTRODUCTION

The Project “Preservation, Safeguard and Valorization of Masonry Decorations in the Architectural Historical Heritage of Piedmont” – named RE-FRESCOS – was approved by the Piedmont Regional Government (Italy) in August 2009 [1]. It involves the main theme of the Conservation of the Piedmont Artistic Heritage and particularly the safeguard of the historical site of the Sacred Mountain of Varallo (Fig. 1).

The research activity of the RE-FRESCOS project is multidisciplinary and is developed by some Departments of the Politecnico di Torino, the Thermodynamic Division of the National Institute of

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Metrological Research (INRIM) and the regional authority of the Special Nature Reserve of the Sacred Mountain of Varallo. This cooperation is addressed to the employment of non-invasive monitoring methodologies to get a precise damage assessment of historical structures, decorated surfaces and terracotta statues belonging to this site, which is in the UNESCO World Heritage List since 2003. The physical-chemical decay and the damage evolution of materials, constituting the decorated surfaces and the structural supports, can be caused by infiltrations of water, thermo-elastic stresses, or seismic and environmental vibrations. The physical-chemical degradation has to be dealt with Materials Science and Chemical Engineering techniques [2]. On the other hand, the instability and the dynamic behaviour of the decorated surfaces, induced also by seismic and environmental vibrations, can be investigated by Acoustic Emission technique (AE) using monitoring systems to control continuously and simultaneously different structural supports [3]. The data collected during the in situ experimental tests can be interpreted with Fracture Mechanics models and methodologies [4, 5].

![Fig. 1 The Sacred Mountain of Varallo: View of the Square of Tribunals](image)

## 2. THE SACRED MOUNTAIN OF VARALLO

### 2.1. Brief History

The most ancient Sacred Mountain of Piedmont and Lombardy is situated among the green of the forests at the top of a rocky spur right above the city of Varallo. It consists in 45 Chapels, some of which are isolated, while others are part of monumental groups. They contain over 800 life-size wooden and multicoloured terracotta statues, which represent the Life, the Passion and the Death of Christ.

The Sacred Mountain of Varallo is the work of two great churchmen and of a number of artists headed by Gaudenzio Ferrari [6]. The two churchmen are: the Franciscan Friar, Blessed Bernardino Caimi and St. Charles Borromeo Archbishop of Milan. At Varallo, Fra Bernardino Caimi put into practice the idea that he had been turning over in his mind during his stay in the Holy Land. His aim was to erect buildings that would recall the “Holy Places” of Palestine. Those places evoke the characteristic monuments of Christ’s stay on earth (the Stable at Bethlehem, the House in Nazareth, the Last Supper, Calvary and the Holy Sepulchre). He began his work in 1491 and carried on with it as long as he lived (until the end of 1499), assisted by Gaudenzio Ferrari who continued the idea and decorated a number of chapels with frescos and statues in wood and terracotta.

St. Charles Borromeo appreciated the work already done when he paid a visit to the Sacro Monte in 1578 and, giving the place the appropriate name of “New Jerusalem”, made it more widely known among his contemporaries. Returning there at the end of October 1584, he decided to develop the original idea by building new chapels, which would illustrate the life of Jesus more completely. For the great Bishop of Milan it was an effective mean of his time, giving the population greater religious fervour and protecting them from the heresies that threatened Northern Italy. He utilized the project for the rearrangement of the Sacred Mountain drawn up by the architect Galeazzo Alessi in 1592 and, adapting it to his own plans, gave instructions for the resumption of work.

The work continued until 1765. During the eighteenth century a half dozen new artists added their names to Gaudenzio Ferrari’s: Morazzone, Tazio, the Fiammighini and the Danedi in panting frescos; Giovanni d’Enrico and Tabacchetti for sculpture, to mention only the most well-known of them. St. Charles Borromeo’s idea and efforts made the Sacred Mountain of Varallo the prototype of few other Sacri Monti that arose in the area during the XVII Century. In total, nine sites were built, the most important being Sacred Mountains of Orta, Varese, Oropa, Crea and Locarno.

Today the Sacred Mountain of Varallo continues to be a school of Christian truth and life, while at the same time it is the most precious treasury of art in the Valsesia Valley.
2.2. The Chapel XVII: the Transfiguration of Christ on Mount Tabor
As the first object of investigation with the AE technique, the Chapel XVII of the Sacred Mountain of Varallo is chosen (Fig. 2).
This Chapel houses the scene of the Transfiguration of Christ, who appeared to the Apostles at the foot of the mountain, in radiant light between Elijah and Moses; the Apostles then perform miracles.
This Chapel was also foreseen in the “Book of Mysteries” by Galeazzo Alessi (1565-1569) [6,7], from which the group of sculptures located high on the mountain take inspiration. The relative foundations were already begun in 1572, but the chapel was not completed until the 1660s.
The statues are attributed to Pietro Francesco Petera of Varallo and to Giovanni Soldo of Camasco, who collaborated with Dionigi Bussola, the last dating back to the 1670s, whilst the frescoes (about 1666-1675) are the work of the brothers Montaldo, known as the “Danedi”, also responsible for the decoration of the cupola of the Basilica of Sacro Monte.

Fig. 2 External view of the Chapel XVII (a); internal view of the Mount Tabor installation (b)

3. DAMAGE ANALYSIS OF THE DECORATED SURFACE STRUCTURAL SUPPORTS BY THE AE Technique

3.1. Energy Density Criterion and b-value Analysis of AE Events
The preservation of mural painting heritage is a complex problem that requires the use of non-destructive investigation methodologies to assess the integrity of decorated artworks without altering their state of conservation. A complete diagnosis of crack pattern regarding not only the external decorated surface but also the internal support is of great importance due to the criticality of internal defects and damage phenomena, which may suddenly degenerate into irreversible failures [8, 9].
A great deal of non-destructive techniques work by introducing some type of energy into the system to be analyzed. On the contrary, in AE tests, the input is the mechanical energy release generated by the material itself during the damage evolution, so that no perturbation is induced and the integrity of the system may be guaranteed. By monitoring the support of a decorated surface by means of the AE technique, it becomes possible to detect the occurrence and evolution of surface vs. support separation and of stress-induced cracks.
Cracking, in fact, is accompanied by the emission of elastic waves, which propagate through the bulk of the material. These waves can be received and recorded by piezoelectric (PZT) transducers applied to the external surface of the artwork support.
Objective of the research is to use the AE technique to assess the support of the decorated mural surfaces developing the application aspects of this technique, which has been widely studied from a theoretical and experimental point of view by the authors in the safeguard of civil and historical buildings [10-12]. In a first stage, it will be essential to recognize the artwork to be monitored, its conservation state and the severity of its conditions at the beginning of the monitoring and restoration processes. The AE technique makes it also possible to predict and localize the presence of cracks and analyze the damage evolution in supports such as decorated masonry walls and vaults [13].
Acoustic Emission data have been interpreted by means of statistical and fractal analysis, considering the multiscale aspect of cracking phenomena [4]. Consequently, a multiscale criterion to predict the damage evolution has been formulated. Recent developments in fragmentation theories [14], have
shown that the energy $W$ during microcrack propagation is released over a fractal domain comprised between a surface and the specimen volume $V$.

The following size-scaling law has been assumed during the damage process:

$$ W \propto N \propto V^{D_3} $$

In Eq.(1) $D$ is the so-called fractal exponent comprised between 2 and 3, and $N$ is the cumulative number of AE events that the structure provides during the damage monitoring.

The authors have also shown that energy dissipation, as measured with the AE technique during the damaging process, follows the time-scaling law [15]:

$$ W \propto N \propto t^{\beta_t} $$

where $\beta_t$ is the time-scaling exponent for the released energy in the range (0, 3) and $N$ the number of AE events.

By working out the exponent $\beta_t$ from the data obtained during the observation period, we can make a prediction on the structure’s stability conditions: if $\beta_t < 1$ the structure evolves toward stability conditions; if $\beta_t \approx 1$ the process is metastable; if $\beta_t > 1$ the process becomes unstable.

Moreover, a statistical interpretation to the variation of the $b$-value during the evolution of damage detected by AE has been proposed, which is based on a treatment originally proposed by Carpinteri and co-workers [16, 17]. The proposed model captures the transition from the condition of diffused criticality to that of imminent failure localisation.

By analogy with seismic phenomena, in the AE technique the magnitude may be defined as follows:

$$ m = \text{Log}_{10} A_{\text{max}} + f(r) $$

where $A_{\text{max}}$ is the amplitude of the signal expressed in volts, and $f(r)$ is a correction taking into account that the amplitude is a decreasing function of the distance $r$ between the source and the sensor.

In seismology the empirical Gutenberg-Richter’s law [18]:

$$ \text{Log}_{10} N (\geq m) = a - bm \quad \text{or} \quad N (\geq m) = 10^{a-bm} $$

expresses the relationship between magnitude and total number of earthquakes in any given region and time period, and it is one of the most widely used statistical relations to describe the scaling properties of seismicity. In Eq. (4), $N$ is the cumulative number of earthquakes with magnitude $\geq m$ in a given area and within a specific time range, whilst $a$ and $b$ are positive constants varying from a region to another and from a time interval to another. Equation (4) has been used successfully in the AE field to study the scaling laws of AE wave amplitude distribution. This approach evidences the similarity between structural damage phenomena and seismic activities in a given region of the Earth’s crust, extending the applicability of the Gutenberg-Richter’s law to Structural Engineering. According to Eq. (4), the $b$-value changes systematically at different times in the course of the damage process and therefore can be used to estimate damage evolution modalities.

Equation (4) can be rewritten in order to draw a connection between the magnitude $m$ and the size $L$ of the defect associated with a AE event. By analogy with seismic phenomena, the AE crack size-scaling entails the validity of the relationship:

$$ N (\geq L) = cL^{-2b} $$

where $N$ is the cumulative number of AE events generated by source defects with a characteristic linear dimension $\geq L$, $c$ is a constant of proportionality, and $2b = D$ is the fractal dimension of the damage domain.

It has been evidenced that this interpretation rests on the assumption of a dislocation model for the seismic source and requires that $2.0 \leq D \leq 3.0$, i.e., the cracks are distributed in a fractal domain comprised between a surface and the volume of the analysed region [19, 20].

The cumulative distribution (5) is substantially identical to the cumulative distribution proposed by Carpinteri [16], which gives the probability of a defect with size $\geq L$ being present in a body.
\[ P(\geq L) \propto L^{-\gamma} \]

Therefore, the number of defects with size \( \geq L \) is:

\[ N'(\geq L) = cL^{-\gamma} \]

where \( \gamma \) is a statistical exponent measuring the degree of disorder, i.e., the scatter in the defect size distribution, and \( c \) is a constant of proportionality. By equating distributions (5) and (7) it is found that: \( 2b = \gamma \). At the collapse, the size of the maximum defect is proportional to the characteristic size of the structure. As shown by Carpinteri and co-workers [17], the related cumulative defect size distribution (referred to as self-similarity distribution) is characterized by the exponent \( \gamma = 2.0 \), which corresponds to \( b = 1.0 \). It was also demonstrated by Carpinteri [16] that \( \gamma = 2.0 \) is a lower bound which corresponds to the minimum value \( b = 1.0 \), observed experimentally when the load bearing capacity of a structural member has been exhausted.

Therefore, by determining the \( b \)-value it is possible to identify the energy release modalities in a structural element during the monitoring process. The extreme cases envisaged by Eq. (1) are \( D = 3.0 \), which corresponds to the critical conditions \( b = 1.5 \), when the energy release takes place through small defects homogeneously distributed throughout the volume, and \( D = 2.0 \), which corresponds to \( b = 1.0 \), when energy release takes place on a fracture surface. In the former case diffused damage is observed, whereas in the latter two-dimensional cracks are formed leading to the separation of the structural element.

In the following, the data obtained from the monitoring are mainly interpreted by Equation (2) and (4).

### 3.2. Structural Condition Assessment of the Chapel XVII

As regards the structural integrity, the Chapel XVII shows a vertical crack of about 3.00 m in length and a detachment of frescos both on the North wall, which are the object of the present monitoring campaign by means of AE. Six AE sensors are employed to monitor the damage evolution of the structural support of the decorated surfaces of the Chapel XVII: four are positioned around the vertical crack while 2 are positioned near the frescos detachment (Fig.3). For the sensor pasting on decorated surfaces, a suitable methodology is applied. Moreover, the Chapel XVII shows another vertical crack on the South wall, symmetric of the previous one with respect to the pronao of the building.

![Fig. 3 Chapel XVII: View of the Monitored Damages and Position of the AE Sensors](image)

The monitoring period of the structural supports of the chapel began on April 28, 2011 and ended on June 4, 2011. The results obtained by the application of the AE sensors are presented in Figs. 4 and 5.
As can be seen from Fig. 4, the vertical crack monitored on the North wall of the chapel presents a stable condition during the acquisition period (0.5 < \( \beta_t < 1.0 \)) and a clear distribution of cracks in a surface domain is proved by the \( b \)-value in the range (0.95, 1.10). The evidence for the presence of a large crack is offered by the low frequency signals registered (< 200 kHz): as a matter of facts, considering the velocity as a constant and applying the Lamb ratio [21], the wavelength needs to be larger than that of the maximum inhomogeneity in order for the wave to pass through without significant modifications in its waveform. It is reasonable to assume that for a high frequency wave it is possible only to propagate through a small inhomogeneity; on the contrary for a low frequency wave it is possible also to propagate through a large inhomogeneity [4,22].

Concerning the monitored frescos detachment (Fig. 5), the decorated surface tends to evolve towards metastable conditions (0.5 < \( \beta_t < 1.8 \)) and the signals acquired show high frequency characteristics (< 400 kHz): therefore a distribution of microcracks in fractal domain near to a volume is assumed for the analysed region.
Moreover, a correlation between the specific analysed AE activity and damage of the decorated surface could also be found with respect to different water cycle stages (e.g. immersion, drying and cooling). As a matter of fact, a mortar specimen was monitored by means of AE during 60 minutes of immersion in mineral water (Fig. 6a). The relevant AE activity recorded is due to the effect of salt crystallization and to the specific pore distribution in the mortar bulk [23]. It is worth noting that the evolution of the cumulated AE resembles the kinetics of the capillary rising in the transient regime (Fig. 6b), underlying how the two phenomena are correlated.

![Fig. 6 Cumulated Number of AE Events during Mortar Immersion in Mineral Water (a); dimensionless diagram of the capillary rising. Each curve refers to the dimensionless quantity \( \alpha \) which is function of the sample thickness, sorptivity and potential evaporation of the microenvironment [24] (b)](image_url)

![Fig. 7 Finite Element mesh (a); Principal tensile stress contour on the deformed mesh (b)](image_url)

4. **FINITE ELEMENT MODELLING**

The chapel was discretized exploiting symmetry with three-dimensional linear pyramid elements, accounting for the accurate geometry of the stone masonry structure. On the contrary, the wooden roof structure was considered only as an external load. The mesh of the structure is shown in Fig. 7a. The elastic properties assumed for the masonry, and the density, where respectively equal to: \( E = 2 \times 10^9 \) Pa; \( \nu = 0.3 \); \( \rho = 2000 \) kg/m\(^3\). The elastic analysis allows for a preliminary assessment of the structure. Fig. 7b shows the contour of the principal tensile stress, reported on the deformed shape of the structure. The deformation clearly shows the opening mechanism due to the effect of the pronao, as well as to the thrust of the internal vault that support the mount Tabor installation. The tensile stresses calculated on the internal wall of the chapel, justify the presence of the two symmetric dominant cracks. A more detailed mechanical characterization of the masonry is currently under development to perform the subsequent nonlinear analysis.
5. CONCLUSIONS

The Chapel number 17, dedicated to the Mount Tabor episode of Christ Transfiguration, of the Sacred Mountain of Varallo shows some structural concern due to cracking and some degradation of the high valuable frescos, which tend to detach from the masonry support. In order to assess the evolution of the phenomena, the results of the Acoustic Emission monitoring program of the Chapel have been provided, together with a structural finite element simulation. The Finite Element analysis provided the basic mechanism that is taking place in the chapel, which caused two main cracks in the internal walls. The results of the monitoring show that the large cracks are stable, while the process of detachment of the frescos is evolving cyclically. It seems that the frescos degradation could be mainly related to the diffusion of moisture in the mortar substrate. Some preliminary laboratory tests also confirm that Acoustic Emissions are recorded in mortar samples subjected to moisture diffusion.

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REFERENCES