GUIDELINES

Acoustic Emission Monitoring for Cultural Heritage

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The Getty Conservation Institute (GCI) works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The Institute serves the conservation community through scientific research, education and training, field projects, and the dissemination of information. In all its endeavors, the GCI creates and delivers knowledge that contributes to the conservation of the world's cultural heritage.

Front cover: Positioning of an acoustic emission sensor on a wooden drum to monitor micro-cracking. Drum is courtesy of the UCLA/Getty Program in the Conservation of Archaeological and Ethnographic Materials.
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1. Scope

Acoustic emission (AE) has been identified as a suitable method for the direct monitoring of physical change in cultural heritage objects subject to external or environmentally induced loads. The technique was introduced to the field in the late 1990s (Grossi et al. 1997), and has been consistently used by several research groups. At the Acoustic Emission Experts Meeting, held at the Getty Conservation Institute in November 2017 (Figure 1), a user group (AEGIS: Acoustic Emission Group for Information Sharing) was initiated to address the need for technical guidelines, aid in the alignment of different research projects, and facilitate collaboration through the effective exchange of experimental data.

This document presents technical guidelines for those actively seeking to deploy the acoustic emission technique to trace physical damage as part of monitoring museum collections. It aims to provide comprehensive information about AE equipment, measuring protocols, and methods of data analysis. The advantages and limitations of the technique for detecting, recording, and interpreting damage in museum objects are discussed.

FIGURE 1

Participants in the acoustic emission experts meeting (see the appendix), held at the Getty Conservation Institute in November 2017.

2. Introduction

Acoustic emission monitoring is a method of tracing physical damage in a material or object in which a stress field develops due to a deterioration mechanism. The brittle cracking of material is accompanied by a sudden redistribution of stress, triggering the release of energy in the form of transient elastic waves. These waves propagate through the material and can be recorded by acoustic emission sensors positioned on the surface. Using appropriate equipment and measuring protocols, micro-changes in material structures can be identified and recorded.

Two aspects differentiate acoustic emission from other nondestructive testing techniques. The first is the origin of the signal. Instead of applying energy to the object under examination, the AE method records the energy released by the object. This makes AE particularly suitable for monitoring materials and structures subject to external loads, which can cause the propagation of defects resulting in acoustic emission. The second difference is that AE is associated with dynamic processes or changes in a material. Since changes in features such as cracks can be visibly recorded, AE allows one to discern between developing material defects and those remaining stagnant. Thus, correlations can be drawn between external loads and the resulting micro-damage.

These unique characteristics make AE an attractive tool for tracing and elucidating damage processes in works of art. It has the potential to act as an early warning system, informing staff about environmental events that may be contributing to micro-damage in the collections they care for. Furthermore, AE monitoring results can be used to inform the development of environmental control strategies by verifying the validity of models that predict object damage.

AE monitoring of cultural heritage objects or structures involves advanced equipment and complex data processing and interpretation. Typically, a specialized laboratory or company is needed to implement AE monitoring campaigns for a museum. Success depends on the proper choice and optimum deployment of measuring equipment, as well as proper selection and application of a data analysis methodology. These issues need to be decided jointly by scientists and those responsible for object safety and preservation.

The purpose of this technical guideline is to:

- Provide advice on the application of AE to challenges in the cultural heritage field.
- Discuss best practices for design and implementation of AE monitoring.

Application of acoustic emission to cultural heritage

AE monitoring has become an important nondestructive tool providing insight into the evolution of damage, particularly in brittle materials. It is a robust and highly sensitive technique that is capable of operating in harsh environments and detecting very small fractures:

FIGURE 2
Two AE sensors monitoring a cracked wooden sculpture in the church of Santa Maria Maddalena in Rocca Pietore, Italy.

Jakieła, Bratasz, and Kozłowski (2007) estimated that the microscopic cracking of wood corresponding to $5\mu m^2$ could be detected. It offers high temporal resolution, whereby individual AE events lasting several microseconds can be digitally captured and processed in real time. The technology has rapidly evolved into a tool capable of accurately tracing defects in space and time (Beall 2002). AE has been applied in industrial and academic research to investigate crack propagation, yielding, fatigue, corrosion, and stress corrosion in a variety of materials: metals, building materials, glass, and wood (Raczkowski, Moliński, and Ranachowski 1994; Kowalski, Moliński, and Musielak 2004). The technique is particularly useful as an early warning system when monitoring objects of critical importance, such as liquefied natural gas storage tanks, bridges, or airplanes (Drouillard 1996).

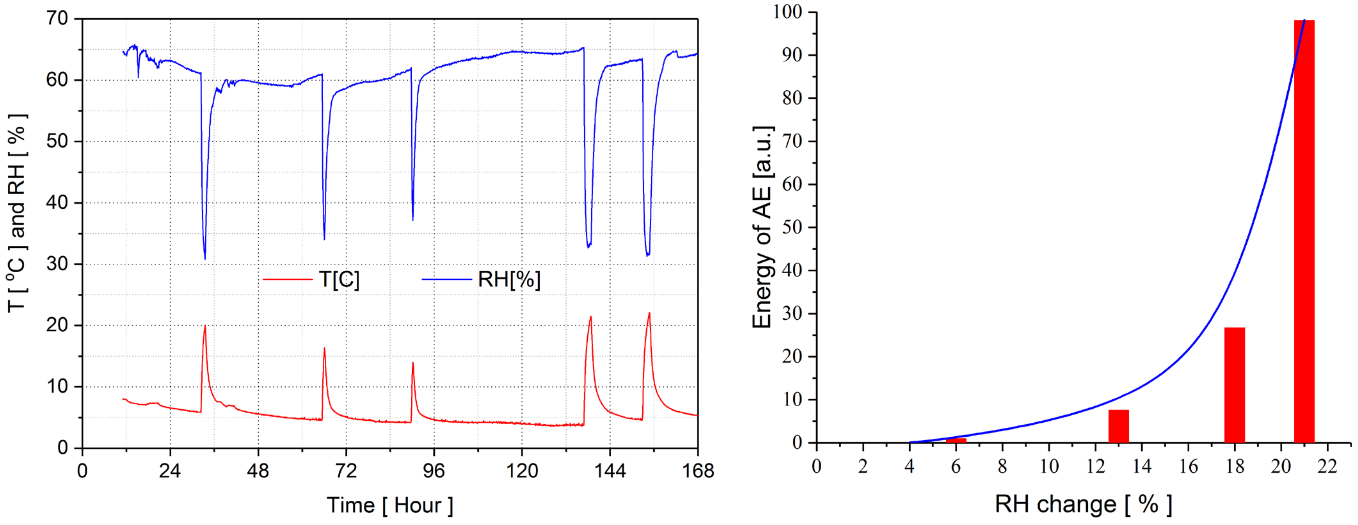
The features which encourage the widespread use of AE in industry are also relevant for various applications in the preservation of cultural heritage (CH). Grossi et al. (1997) conducted the initial AE tests in the CH field, investigating the erosion of historic sandstone caused by salt crystallization. The authors found a lack of correlation between AE energy and observed damage in the material. Later work by Strojecki and Bratasz (2012) showed that a significant number of AE signals was emitted during the reconfiguration of salt crystals in response to changes in relative humidity (RH) or temperature.

Jakieła and Kozłowski (2008) were the first researchers to apply AE monitoring to wooden works of art. During dynamic temperature and RH changes caused by a warm-air heating system, two AE sensors monitored crack propagation in the head of a wooden sculpture (Figure 2), part of a medieval altarpiece in the church of Santa Maria Maddalena in Rocca Pietore, Italy.

In spite of the very long response time of the wooden head (13 cm in diameter), in situ AE monitoring in S. Maria Maddalena showed that the sculpture experienced significant internal stresses and eventual cracking generated by sharp decreases in RH associated with heating. Figure 3 illustrates the rapid increase in total AE energy for drops in RH larger than 15%.

AE monitoring has proved capable of tracing damage development in wooden elements subject to loud environmental factors, such as the playing of historic organs (Bergsten et al. 2010). This is made possible by analyzing the frequency signature of the recorded AE

FIGURE 3
Left: dynamic temperature and RH changes during heating episodes in the church during a winter period; right: total energy of AE events recorded on the wooden altarpiece as a function of the amplitude of the fluctuation in RH during the heating episodes.



signal, which differs for events related to damage and environmental noise. Acoustic signals emitted by the larvae of wood-destroying insects have also been used for detecting infestation in historic buildings (Indrayani et al. 2007) and wooden objects (De Reyer et al. 2005). A positive correlation between AE energy and temperature can indicate the presence of insects, as shown by Łukomski et al. (2017).

In addition to short-term laboratory or in situ experiments, AE may be successfully used for long-term monitoring. Strojecki et al. (2014) successfully performed a two-year acoustic emission monitoring campaign for an eighteenth-century wardrobe in the Gallery of Decorative Art at the National Museum in Krakow, Poland. Analysis of AE data allowed the risk of damage to the object to be quantified as a function of the magnitude of RH fluctuations.

A wide range of additional heritage materials and their associated deterioration processes have been investigated using AE. AE studies on non-wooden materials include assessments of the cracking of historic glass with observable crizzling during changing temperature conditions; cracking of enamel in response to temperature changes (Studer 2012, Thickett 2018); the erosion of clay containing sandstone during wetting-drying cycles (Bratasz et al. 2008); and shrinkage cracking in hydrating historic cement pastes and mortars (Wilk, Bratasz, and Kozłowski 2013).

3. Acoustic emission monitoring

AE signals

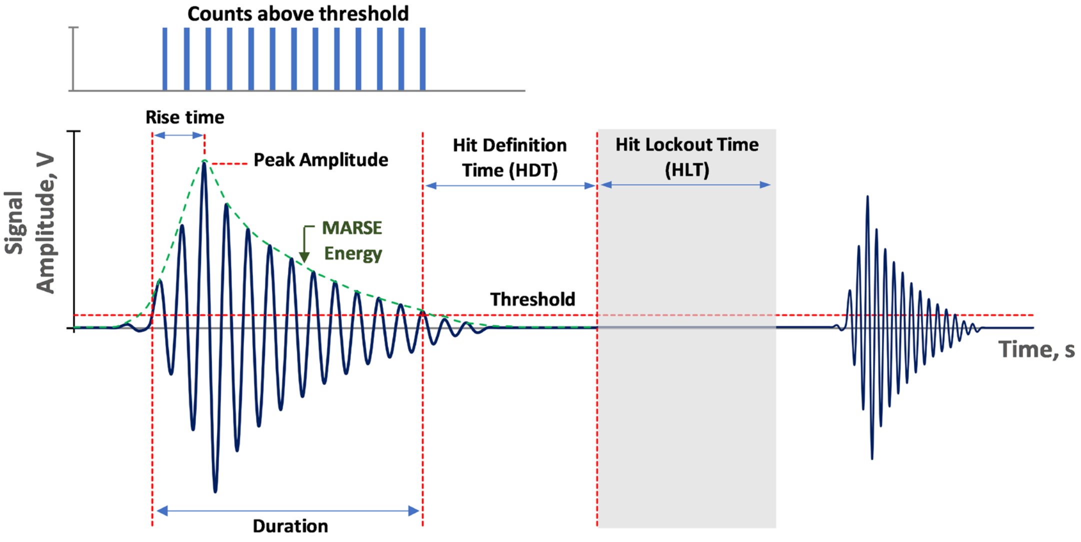
Acoustic emission testing uses piezoelectric sensors on the surface of a material to detect ultrasonic elastic waves at frequencies usually ranging from 1 kHz to 1 MHz. Mechanical deformation and fracture are the primary sources of AE. Initiation of these phenomena involves subjecting the material to a stress-inducing event, such as an applied force, changing temperature or moisture content, or chemical action. To a lesser extent, AE may be triggered by friction, phase transformation, corrosion, and slip and twinning in metals.

Each test involves measurement and analysis of the waveform for each event or 'hit'. Prior to conducting such a test, it is essential to define the attributes that will trigger or exclude a hit, and set limits on the duration of the analysis window. The signal threshold defines the initiation of an event and influences the end point. Waveforms below this value are ignored, while those above are logged as a hit. The threshold value and signal amplitude are often presented in decibel units defined as

$$dB_{AE} = 20\log\left(\frac{V_s}{V_{ref}}\right)$$

where V_{ref} is commonly 1 µV, and V_s is the signal voltage before amplification. As an example, a voltage threshold of $V_s = 40$ µV results in $dB_{AE} = 32$ dB from the above equation. The addition of a preamplifier with a gain of 40 dB will result in amplification of the V_s signal 100 times: $V_a = 40\ \mu V \times 10^{(40\ dB/20)} = 4{,}000\ \mu V$ (or 4 mV) at this threshold. Figure 4 illustrates a typical burst-type waveform that is frequently encountered in AE testing. Waveform sampling is triggered when the signal crosses the predefined threshold, which

FIGURE 4
Simplified illustration of a burst-type AE signal with settings and outputs denoted.



is highlighted by the first vertical red line. Several other parameters are then used to adjust the waveform capture: hit definition time (HDT), hit lockout time (HLT), peak detection time (PDT), and max duration.

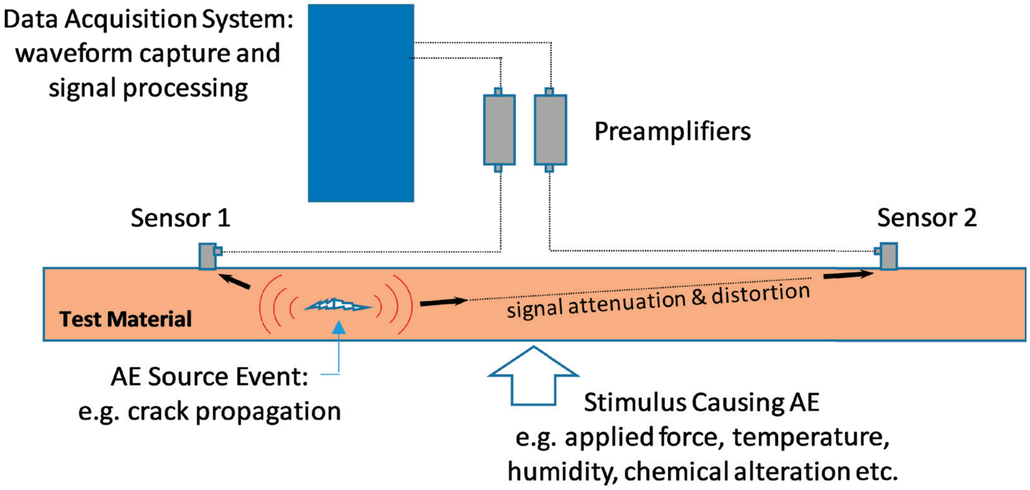
Guidelines on AE settings are available in the literature (Pollock 2003) and briefly summarized here. The HDT is a timing parameter used to trigger the end of waveform capture. During an active hit, an internal clock is set to zero every time the signal exceeds the threshold, and the end of the event is defined as the last threshold crossing when HDT elapses. After the hit is complete, the HLT value provides a programmable delay before another event can be triggered on the respective channel. Two different approaches are commonly used for HLT in practice: set HLT = HDT, or use the minimum value possible. Early AE systems were hampered by a significant delay to accommodate data processing; modern systems are sufficiently fast to permit a very short HLT interval. A third timing parameter, PDT, indicates the window of time in which a new peak amplitude can be defined (often selected as an upper limit of HDT/2). Finally, the maximum duration variable sets the total time in which a waveform can be captured if the signal remains above the threshold and HDT is not yet triggered. Other important factors for consideration are waveform sampling rate (considering the Nyquist Theorem), and frequency filter settings.

Systems and sensors

Figure 5 illustrates the typical components of an AE experiment: a multi-channel data acquisition system (DAQ), piezoelectric sensors with a chosen frequency response, and preamplifiers with a fixed or adjustable gain (40dB is common). In this example, two sensors are fixed to the material surface—directly or via a coupling agent—for the detection of crack propagation caused by an externally applied stress. Sensor 1 receives the signal first due to its proximity to the source, while Sensor 2 receives a delayed signal with lower amplitude and higher distortion due to the frequency-dependent attenuation over the distance travelled through the test material. Factors such as anisotropy and material boundaries will also influence signal characteristics.

When selecting a system for AE monitoring, several factors should be taken into consideration. For any type of acoustic emission experiment, reliable hardware and software flexible enough to perform different types of data analysis are crucial. A multichannel sys-

FIGURE 5
Typical components of an acoustic emission system.



tem, compatible with various types of AE sensors, is strongly recommended. Such a system should also be able to record external analog signals, which can be used to monitor conditions of interest (e.g., temperature, relative humidity, and load) or trigger measurements.

For field applications of AE, it is prudent to consider using an internet connection. This makes it possible to review the results of monitoring in real time, and remotely adjust sampling parameters as needed. Additional factors for in situ operation of an AE system include system safety (removal of any high voltage or heating elements close to AE sensors), and the use of unobtrusive AE sensor holders.

The AE systems produced by Vallen Systeme GmbH and Physical Acoustic Corporation fulfill the above requirements, and are commonly used for scientific research and nondestructive monitoring. Other commercially available products or custom-built systems may also be considered, especially for applications requiring a specific approach.

AE sensors convert dynamic surface motion to an electrical voltage signal. The transducer elements of each sensor are made of piezoelectric crystals with a specific operating frequency and sensitivity. Recorded AE signals, therefore, are not only characterized by the source process and the attenuation of acoustic waves traveling through a material, but also by the AE sensor and the selected settings in the AE hardware (Figure 6).

In the frequency domain, the primary influence on the recorded AE signal comes from the resonant behavior of the piezoelectric AE transducer. To comprehensively characterize the damage process, it is preferable to employ a sensor that is highly sensitive, has a large signal-to-noise ratio, and possesses a uniform response over a wide range of frequencies. The latter is particularly important for applications in which the categorization of measured AE signals is based on their frequency signature. An example of a sensor that meets these requirements, including broadband high-fidelity, is the point-contact piezoelectric transducer by Glaser (KRNBB-PC, KRN Services, Inc., USA) (McLaskey and Glaser 2012)

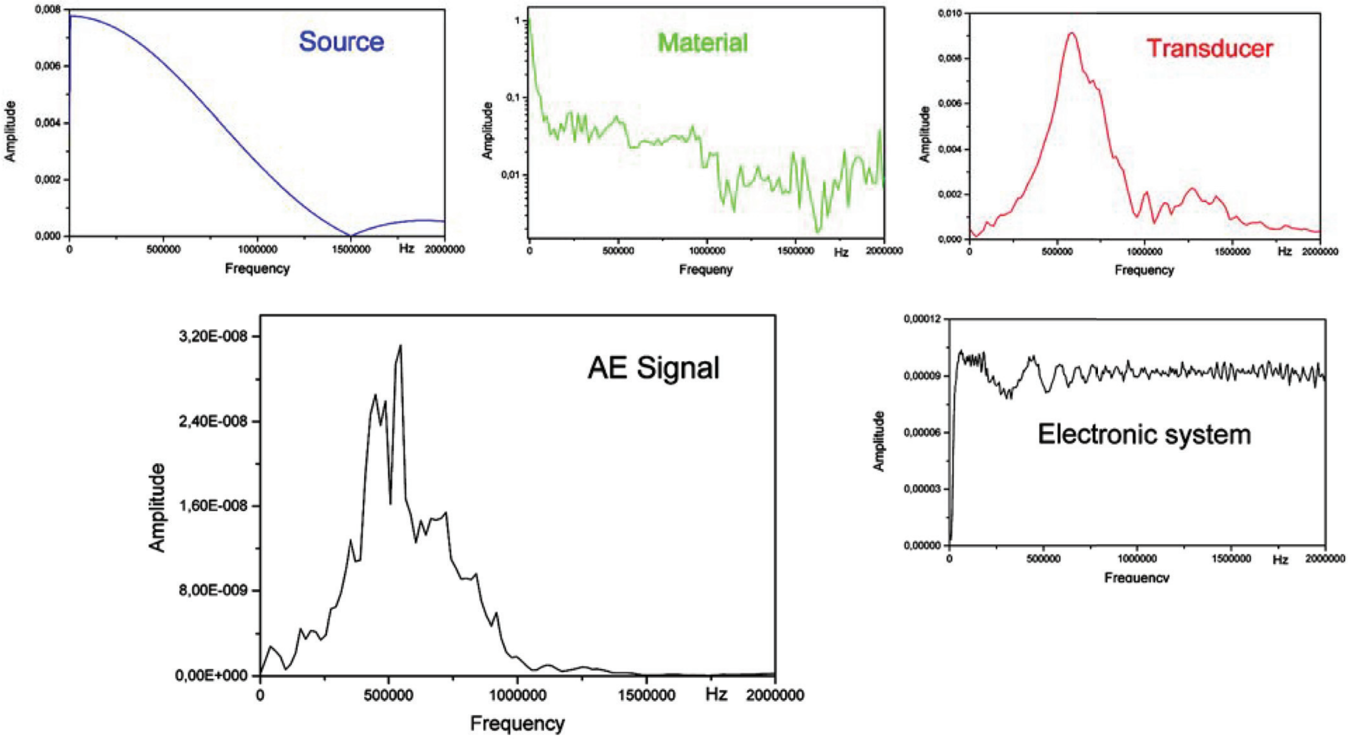


FIGURE 6
Contributions of different transfer-functions of source, material, sensor and acoustic emission electronic system obtained from FEM-simulations to the final (recorded) acoustic emission signals (Bohse 2004).

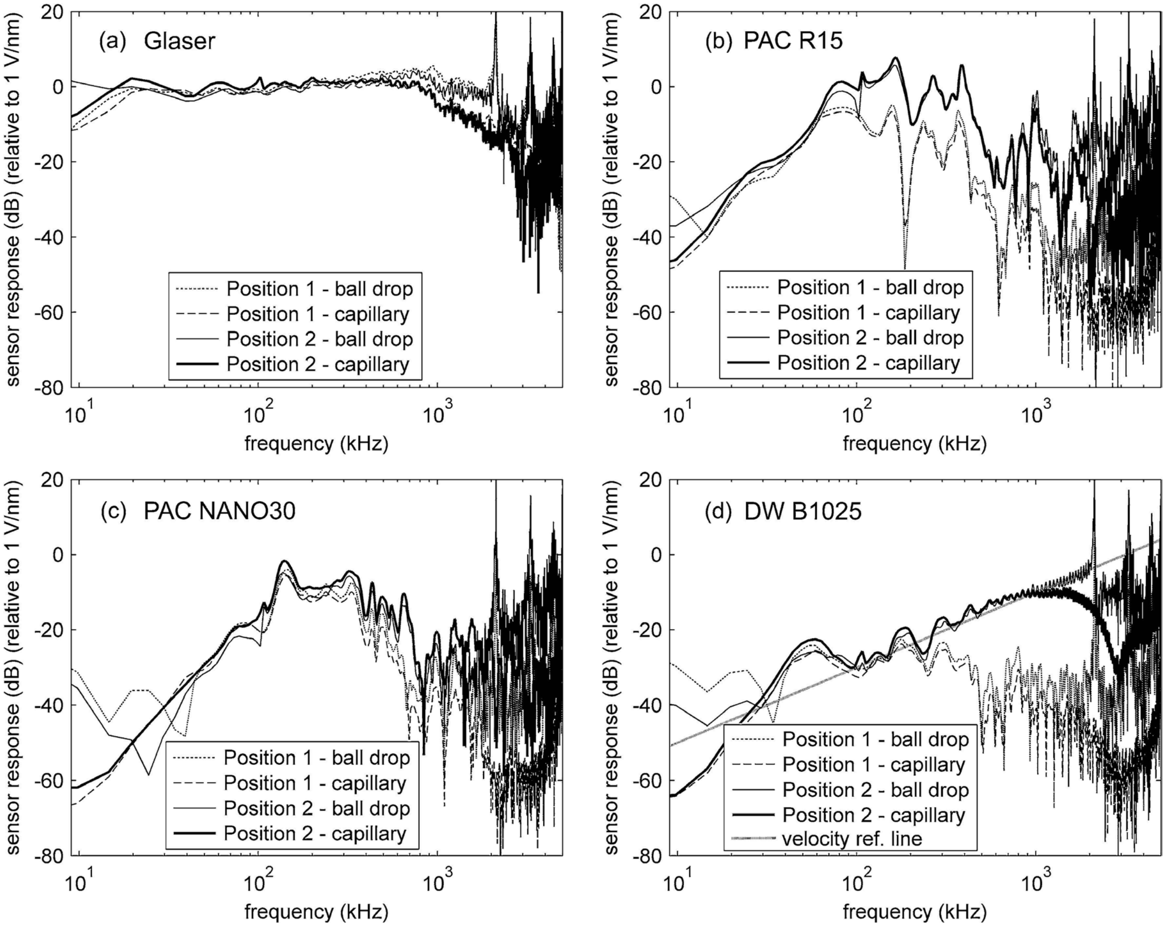


FIGURE 7
a) The frequency response of point-contact sensor of Glaser design with 'flat' frequency response in a range between 10 kHz and 1 MHz; b, c) response of narrow-band: PAC-R15 and PAC nano30 AE sensors; d) response of broadband DW B1025 AE sensor. Results of different calibration methods are compared for each sensor (McLaskey and Glaser 2012).

(Figure 7). The disadvantage of using the Glaser sensor is related to its point-contact shape, which requires use of a threaded housing to gently secure the sensor to the surface (Figure 8).

In specific cases, particularly for long-term monitoring of well-known materials, it may be preferable to use other AE sensor types. For example, Jakieła and Kozłowski (2008) and Strojecki, Łukomski, et al. (2013) verified that AE signals resulting from the destruction of wooden objects were characterized by a significant amount of high frequencies (above 100 KHz), whereas other 'nondestructive' processes, like friction, produced low-frequency

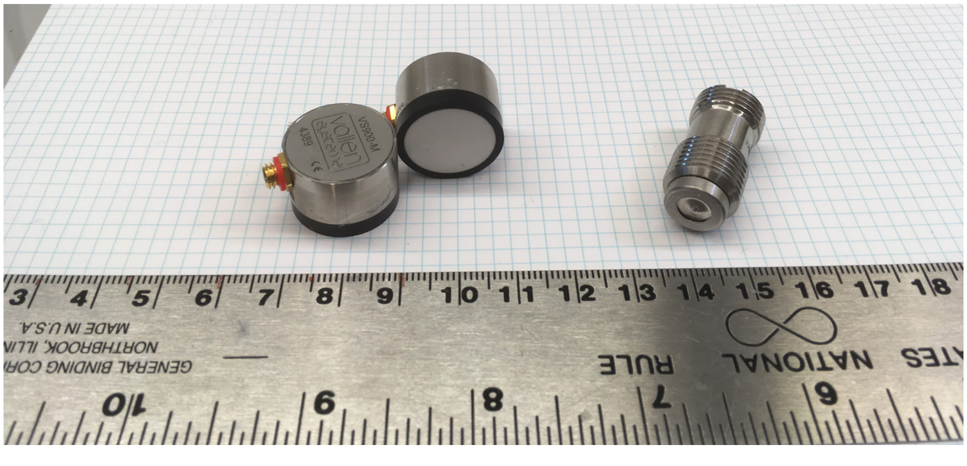


FIGURE 8
Left: wide band PCA WD sensors; right: point contact KRNBB-PC, KRN Services sensor.

signals. Therefore, it may be suitable to employ a resonant sensor with a stronger response at higher frequencies, reducing the influence of low-frequency signals from a noisy environment that are not related to wood fracture.

Attenuation of AE signals

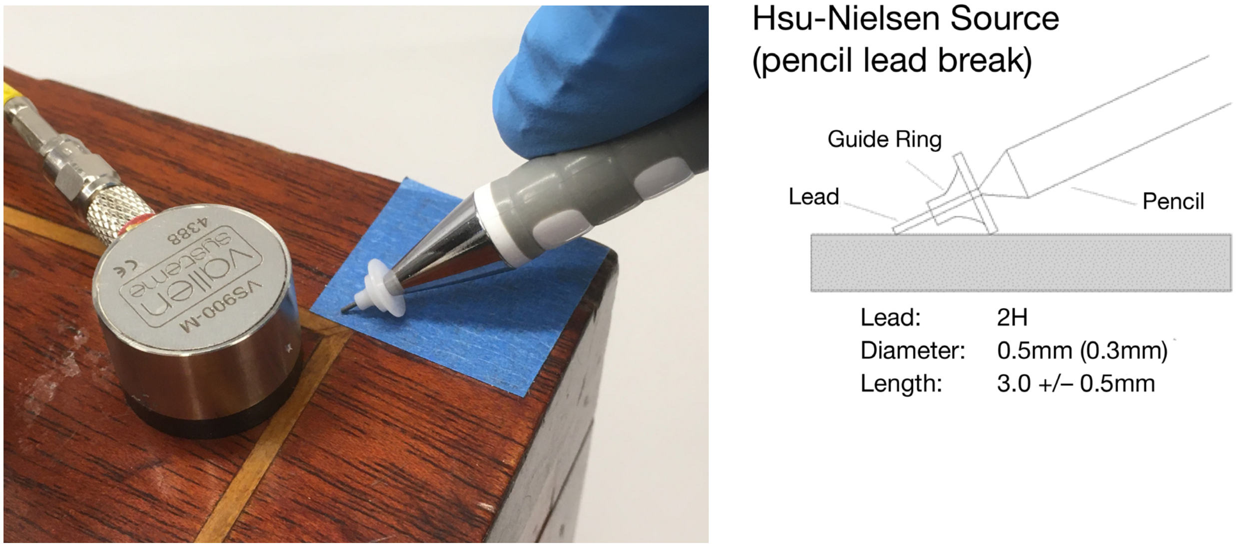
Understanding the attenuation of acoustic waves in materials is crucial for effectively designing an AE monitoring protocol, selecting appropriate sensors and their placement, and choosing optimum methods of data analysis and interpretation.

The degree of acoustic wave attenuation is material- and frequency-specific. Taking into account the conservation of energy in a three-dimensional boundless volume, the amplitude of an acoustic wave decreases to half when the distance from the source is doubled. Further signal attenuation results from the damping characteristics of the material itself (kinetic energy is absorbed and converted into heat) and wave scattering from inherent material defects or boundaries.

The effect of AE signal attenuation can be roughly evaluated by performing ‘pencil lead break’ (PLB) tests at different distances from the sensor (Figure 9). During this test, 2H pencil lead housed in a cone-shaped Teflon shoe (Hsu-Nielson Source) is broken on the material surface, creating a broadband acoustic wave. A PLB test can reveal how the amplitude of the acoustic signal changes with distance from the source and for specific frequencies. It is also useful to ascertain if areas of interest are within the detection range of the AE sensor. It should be noted, however, that PLB signals are typically much stronger than those recorded during a monitoring campaign.

For an orthotropic material like wood, the attenuation of frequencies transmitted through the material is different in each anatomical direction and depends on the frequency range (Figure 10). In the case of dry Japanese Cedar wood (density of 360 kg/m^3), the attenuation of longitudinal waves with the frequency of 0.5 MHz is equal to 2.1, 4.7, and 8.5 dB per 1 cm for the longitudinal (along the trunk, L), radial (R), and tangential (T) directions, respectively (Bucur and Feeney 1992). Thus, the amplitude of the ultrasonic signal after travelling through 10 cm of wood decreases by a factor of 12.7, 17.2, and 26.7 for the L, R, and T direction, respectively.

FIGURE 9
Left: PLB test on a wooden box (blue tape applied for protecting the surface); right: schematic from *Nondestructive Testing Encyclopedia*: https://www.ndt.net/ndtaz/content.php?id=474.



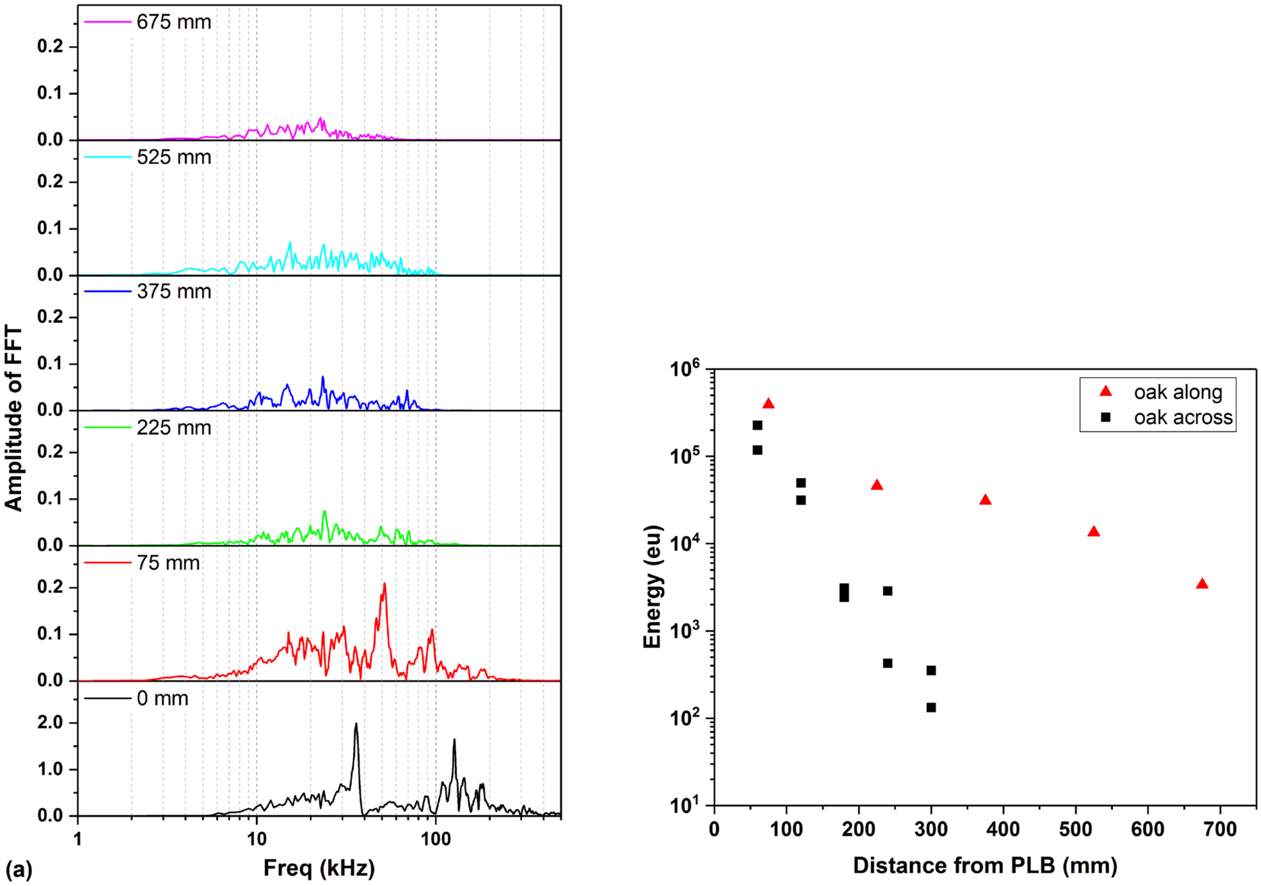


FIGURE 10
Illustration of attenuation of AE signal in oak wood. Left: frequency spectrum of PLB test measured at different distances from the source; right: energy of recorded signal for the same process (Łukomski et al. 2017).

Compared to wood, mineral materials have a higher density with a more homogenous and isotropic structure, resulting in much less attenuation of ultrasound waves. In the case of gabbro rock, which has a density nearly 10 times greater than wood, the amplitude of a 2 MHz ultrasound wave will decrease by a factor of 10.6 after travelling through 10 cm of material (Liu and Ahrens 1997). Since the attenuation is lower for longer waves, the resulting attenuation for a 0.5 MHz wave may be decreased by a factor of 3 to 5 for a similar travel distance. For less dense materials like sandstone, marble, and limestone (densities from 2200 to 2800 kg/m^3), ultrasound waves in the 0.5 MHz range show an attenuation falling between that of the L direction of wood and that of gabbro rock.

Positioning and mounting sensors

Due to the limited distance from the source at which acoustic waves can be detected, it is important to strategically select where AE sensors should be located. Areas most at risk of damage can be defined by understanding the structure and materials of the object. Conservator judgement and knowledge about past damage and conservation treatments are crucial at this stage. In practice, it is common to position sensors close to the tips of existing cracks, which represent geometric discontinuities where a local increase in the stress field may be observed. The advantage of such an approach is that AE monitoring can be highly sensitive, which is conducive to its use as an early warning system.

In addition to distance from the signal source, the sensitivity of AE recording depends on the proper contact between the sensor and the surface of the monitored object. For industrial applications, it is common to use various glues or magnetic clamps (in the case of application on metal surfaces) to ensure sound contact. Binding media, such as ultrasonic gels, are also used to maximize the transfer of acoustic waves from the surface to the sensor's piezoelectric crystal.

In cultural heritage applications, the range of clamping methods is often restricted. Monitoring art objects like sculpture, furniture elements, or paintings usually requires alternative methods of sensor-object attachment to ensure that the mounting is reversible. Methods relying on gently pressing the sensor to the surface using springs, rubber bands, or weight is preferable. In case of uneven surfaces, a curable clay-like material (e.g. modeling clay) may be used as a binding medium: it will not contaminate the surface of the object, and provides good intermediate contact between the sensor and the surface. Examples of different mounting methods are shown in Figures 2 and 11. The quality of contact between the sensor and the monitored surface can be assessed by PLB tests performed on the surface close to the sensor. This test should be repeated frequently to determine if the extent of contact has changed during monitoring: contact between the sensor and the surface may be compromised due to the sensor's gravitational weight, creep of the mounting glue, or pulling of the sensor cable.

FIGURE 11
Examples of sensor-to-object attachment in the case of two wooden sculptures: the *Risen Christ* (left) and the *Madonna from Krużlowa* (right) from the National Museum in Krakow, Poland. AE sensors are pressed to the upper and lower part of the *Risen Christ* statue by the system of metal rails. The AE sensor is attached to the inner side of the *Madonna from Krużlowa*'s hand by means of a Japanese tissue paper.

4. Data analysis and interpretation

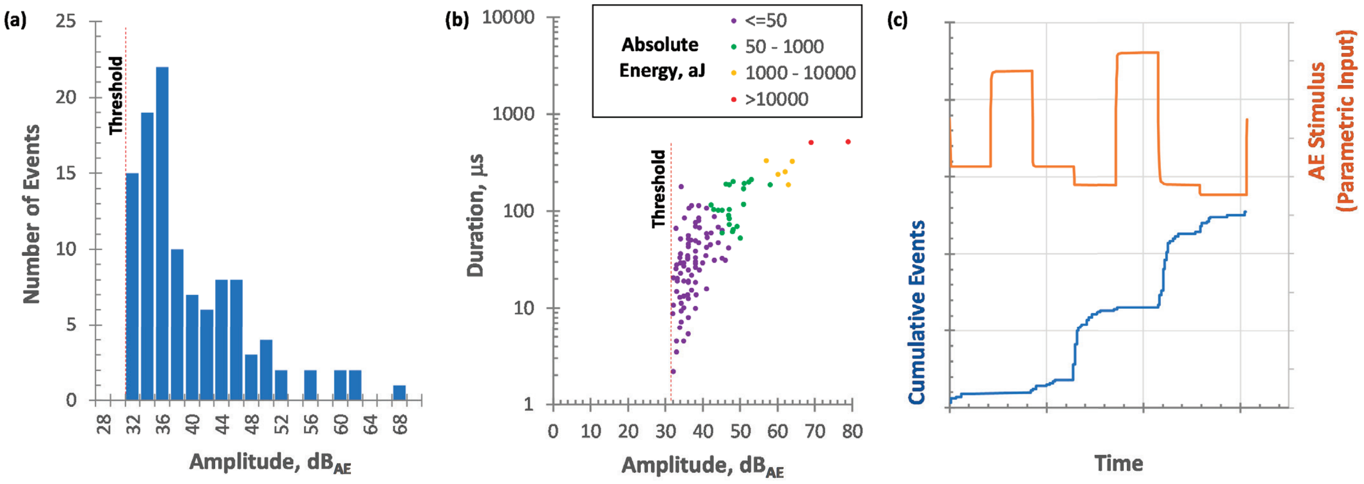
Data processing

With early AE systems, it was not practical to store waveform data; therefore, basic signal features were the sole source of information collected. Modern AE systems allow for the capture of full waveforms, in addition to calculating a wide range of signal parameters. Common signal features of interest include peak amplitude, duration, rise time, frequency, and energy. In practice, the method of calculation for each feature may differ based on choice of measurement protocol and software. Available resources (ASTM 2018; Shiotani 2008) summarize the various AE terminology, and a selected glossary is provided at the end of this document for convenience. Note that parameters for similar event features may have different methods of calculation, and varied uses for data interpretation. Figure 12 shows a selection of plots illustrating possible data visualization choices. Parameters may be compared as histogram plots (number of events versus amplitude bins), x-y scatter (duration vs. amplitude), or cumulative data (events or energy) as a function of time.

The monitoring and analysis of AE data is typically a multi-step process, assisted by plots of several signal parameter relationships. Representations of AE activity (number or rate of AE events) and intensity (AE energy or amplitude) as a function of time are typically used to examine the ongoing damage process. In contrast, plots showing counts versus amplitude, duration versus amplitude, and counts versus duration are suitable for evaluating the quality of data collected. An example of such an evaluation is presented in Figure 12b, which shows amplitude and duration for each recorded event. The threshold was selected to eliminate the collection of noise signals, which would fall on the left side of the vertical line. For the collected data points, it is necessary to isolate those related to damage events from non-damage (e.g., friction between wood fibers). This next phase of interpretation may

FIGURE 12

Example graphical representations of AE waveform parameters: a) histogram of AE events (hits) versus maximum amplitude; b) x-y scatterplot of duration versus amplitude, color-coded by absolute energy; c) cumulative events with time, overlaid with a controlled parametric input (e.g. fluctuating relative humidity) inducing the events.



involve an evaluation of other signal characteristics, such as frequency centroid and absolute energy, or the study of individual waveforms. As an example in the analysis of wooden objects, a test involving AE monitoring of a controlled fracture of a veneer sample can quickly provide valuable comparative data. Further methods of interpretation are outlined in the following sections.

Interpretation of recorded AE

Correlation with external and internal stresses

The most common means of interpreting AE data is to correlate the measured signal with stresses exerted on the material during the monitoring period. Depending on the complexity of the monitoring design and availability of sufficient computer memory, it is possible to analyze the rate of AE (number of recorded events per unit time) or energy related to each individual AE event. The first method provides an indication of the time of micro fracture, whereas the latter allows for the evaluation of the extent of damage based on laboratory calibration.

While museum objects are rarely subjected to external forces, this may occur when a particular method of presentation (e.g., mounting for exhibition) is required for an artwork. Conversely, internal stresses can build up within objects that are subject to inappropriate environmental conditions, which may cause fracturing of its materials. This environmentally induced stress can be effectively monitored by AE.

Environment-related AE

Variations of temperature and relative humidity pose a potential risk for art collections. Many vulnerable cultural objects are composed of complex multi-layer structures that contain humidity-sensitive materials. These materials respond to changes in ambient RH and temperature, shrinking and swelling when they lose and gain moisture, respectively. The mismatch in response of adjacent individual materials can induce tensile or compressive stresses in the structure of art objects, creating the potential for deformation, cracking, and delamination of layers. A moisture-sensitive object may also experience stress due to restraint of its dimensional response by a rigid construction technique: restriction of the object’s free movement can cause deformation and cracking.

In addition to its effect on dimensional response, variations in moisture and temperature can also lead to cycles of salt crystallization or phase transitions, which are known to result in the fracture of contaminated wood, stone, and brick. Changes of temperature and humidity also influence the metabolism of wood-eating insects, resulting in a higher level of biological activity and increased AE signals.

Response time of materials

The response time of material to variations in temperature and humidity is not immediate due to limited thermal and moisture diffusivity, respectively. Since the development of stresses results from the material response, AE signals are often not correlated directly with instantaneous temperature and humidity, but rather account for the delayed response of the object. This can be practically examined by correlating the recorded AE signals with a simple running average of temperature and humidity, for which the appropriate time window is empirically determined. The advantage of using a running average is that short-term fluctuations are smoothed while the longer-term cycles, to which the material in question might more realistically respond, are emphasized. It should be noted, however, that a running average is just one correlation technique, and different methods of relating external conditions to resulting damage should be explored for monitored objects.

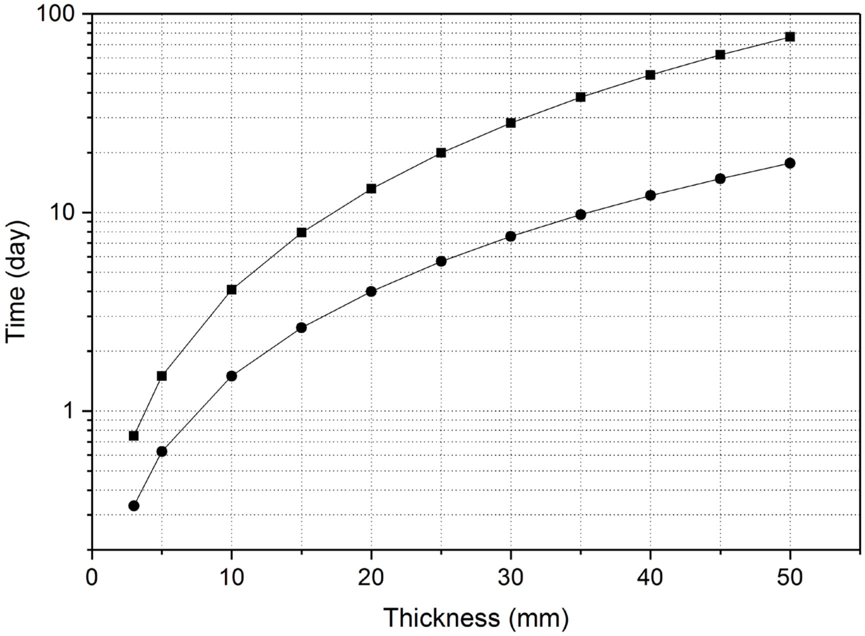
All materials respond dimensionally to temperature variation. This thermal response is relatively small and fast in comparison to moisture-induced swelling and shrinking. For museum artifacts of low to moderate thickness, it is often practical to assume that equilibration with the ambient temperature occurs in the range of several minutes or hours. The humidity-induced response of an object is, however, more complicated. The time of response is determined by a relatively slow diffusion of water into the material—this rate is dependent on the material type, its density and porosity, moisture content, and the air speed in the vicinity of the object. Temperature influences the humidity response of the object, with higher temperatures resulting in faster moisture diffusion rates.

The shape and size of an object is also a crucial factor in its response to humidity. A thick, bulky object will respond more slowly to a change in ambient relative humidity than a thin object made with the same material. At a given depth from the surface, both objects will respond at the same rate; however, it will take longer for the thicker object to reach moisture equilibrium with the surrounding air. Response time is also dependent upon the availability of surface area for moisture exchange. Objects coated with a low vapor permeability layer will exchange moisture vapor with the surrounding air more slowly than uncoated objects, and, thus, will be less affected by RH fluctuations.

Figure 13 shows the relationship between the thickness of a coated and uncoated wooden panel and the time it takes to reach 63.2% of its final (asymptotic) dimensional response when RH is changed from 35 to 70% (Rachwał et al. 2012). Note that the time corresponding to 95% of the total asymptotic response is three times bigger than the time presented in Figure 13.

The delay between a change of environmental conditions and the resulting fracture of an object depends on the type of restraint. The restraint may be a rigid construction that limits movement, or an interface with a less responsive material. It may also occur internally from a gradient of moisture through an object: e.g., under low RH conditions when outer

FIGURE 13
Response time of panels with one face (■) and both faces (●) uncoated and subjected to a steep RH change from 35 to 70% as a function of panel thickness (Rachwał et al. 2012).



sections dry before the interior. For externally restrained objects, damage may appear after the bulk of the material has had sufficient time to respond to the humidity change, whereas the highest risk of damage for internally restrained objects coincides with the development of a maximum moisture gradient within the object. As a consequence, defining the delay between environmental response and resulting fracture requires an understanding of the object and its materials, as well as the processes that lead to damage.

When the response time of a monitored object is known or can be reliably evaluated, it is feasible to use this value to analyze correlations. When response time cannot be evaluated on the basis of a material-specific moisture diffusion coefficient, or when the evaluation is complicated by object geometry, a range of response times should be analyzed. An example of such an analysis was presented in Strojecki et al. (2014). Figure 14 presents AE energy measured in the side panel of an 18th-century wooden wardrobe, at a growing crack caused by fluctuations in relative humidity. In the figure, a positive correlation between AE energy and RH level was found for a response time of one week. No such correlation was observed for longer response times.

When defining response time based on its correlation with AE monitoring, it should be assumed that factors other than RH instability have a negligible impact on the damage development that is recorded. If this were not the case, having no a priori knowledge of an object's response time would make it difficult to determine any correlation between RH fluctuations and damage development without improving the signal-to-noise ratio. In practice, the response time determined by examination of the data should agree with reasonable estimations for the monitored object. In the prior example, the empirically determined response time of one week corresponds well with estimated values for a 10 mm thick wooden panel. Once the time delay between changes of external conditions and the occurrence of damage has been determined, it is possible to investigate the correlation between microclimatic conditions and micro-damage.

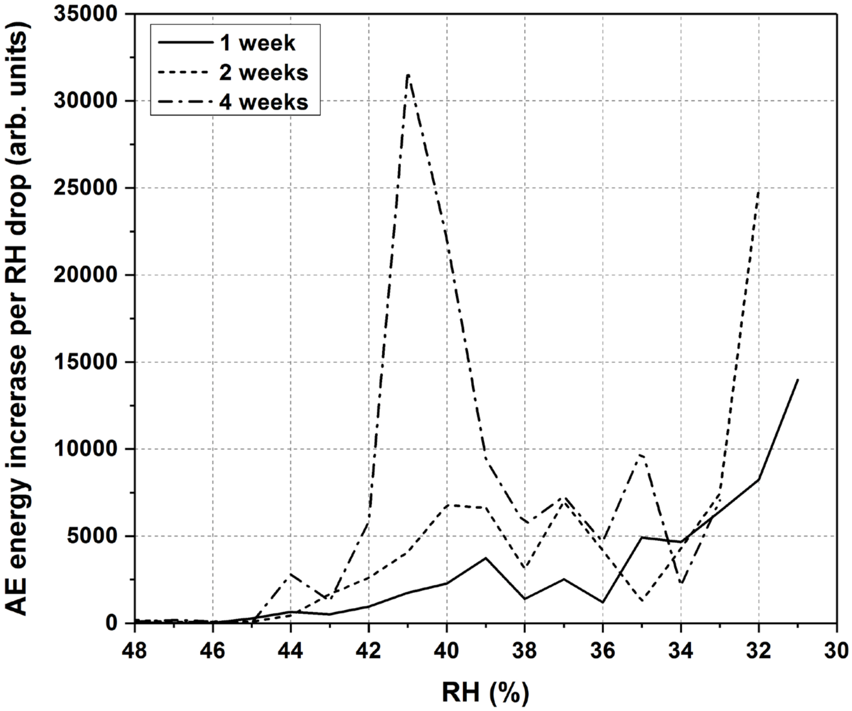


FIGURE 14
Plots of recorded AE energy averaged per RH drop to a given RH level for three different response times.

Linking AE with damage

The energy of AE events is the primary metric for determining the extent of fracture in material structures. Therefore, it is desirable to calibrate the AE method to enable quantification of the measured AE energy in terms of damage of the monitored object. Calibration requires the correlation of AE energy—measured during a destructive process—with the quantified amount of material fracture, measured by an independent technique. A calibration procedure conducted by Strojecki et al. (2014) and Łukomski et al. (2017) used a digital camera to quantify the cracking of oak wood when subjected to an increasing load, and defined a correlation between crack development and measured AE energy (Figures 15 and 16). Applying such a calibration to data collected during the monitoring of a gallery's art objects makes it possible to quantify the risk of mechanical damage engendered by different climate control strategies.

However, such calibration procedures are only valid for specific materials and measuring systems. The sensitivity of the measuring system depends on the types of AE sensor, signal amplification, and signal filtering that are employed. To maximize its relevance to monitored artifacts, an AE calibration should be performed on samples of similar materials using the same instrumental set-up (i.e., sensor, amplifier, and frequency filter) used during monitoring. Calibration is further complicated by the attenuation of the acoustic signal as it travels through the material: while monitoring the object, one may not know the distance between the signal source and the sensor. Attenuation of the signal also depends on wood grain orientation in the tested sample.

In summary, while calibration of the AE system is recommended, its limited accuracy and the specificity of choices in hardware should be taken into consideration. It should also be remembered that AE monitoring can be meaningful without an AE energy calibration, as information about the extent of damage is relative, and one can still distinguish between events that cause damage and those that do not.

FIGURE 15

The set-up for AE calibration on oak, which introduces an artificial crack that is propagated by movement of the universal testing machine clamps. Crack propagation is recorded by an AE sensor and a CCD camera.

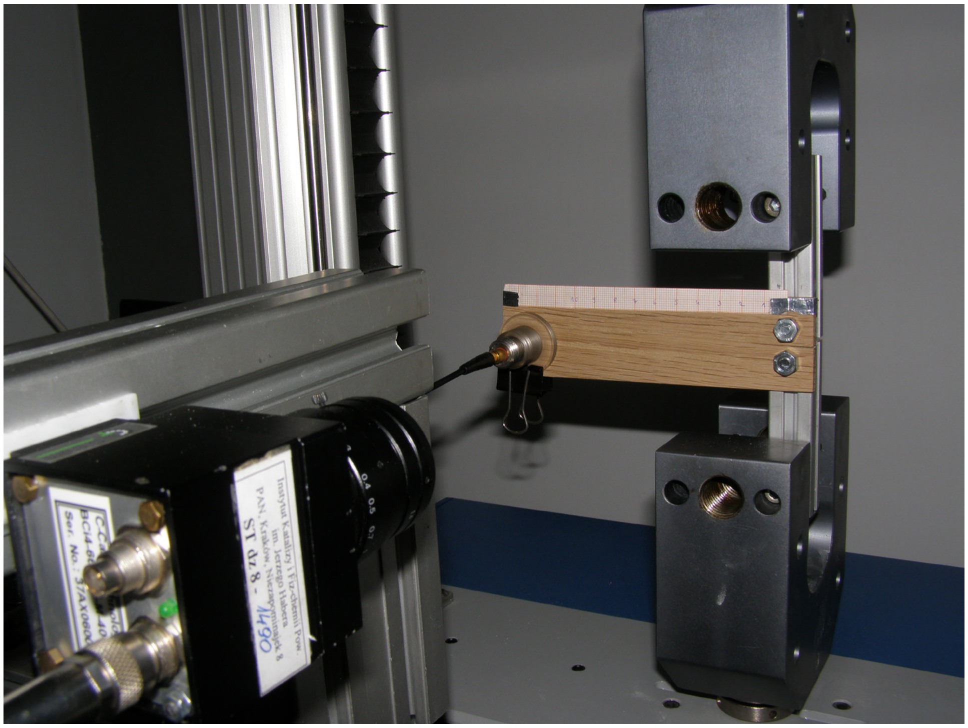
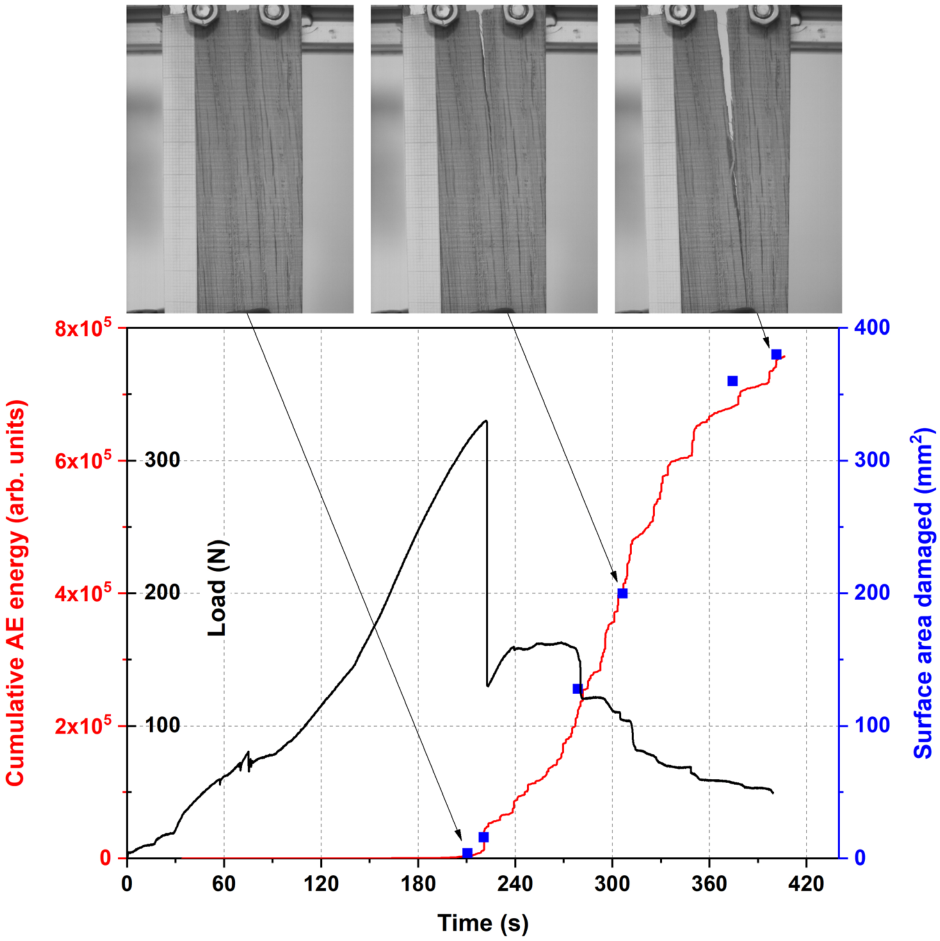


FIGURE 16
Results of a calibration measurement for an oak wood sample showing applied load (black line), crack propagation in mm² (blue squares), and cumulative AE energy in arbitrary units (red line). The three photos correspond to the initial, intermediate, and final phase of cracking.



5. Additional considerations

Noise reduction strategies

When monitoring art objects in a gallery or historic site, low levels of AE signal are expected in comparison to environmental noise. This circumstance requires effective filtering of signals resulting from processes other than material fracture.

When planning for long-term monitoring, it is good practice to first conduct trial monitoring using a low threshold of signal trigger amplitude without frequency filtering. After a few weeks, one will understand the characteristics of baseline environmental noise, and be able to select proper amplitude thresholds (to reduce the amount of recorded noise) and frequency filters. Selection of frequency filters depends mainly on the material composition of the monitored object. It has been demonstrated that for wood (Jakieła and Kozłowski 2008; Strojecki, Łukomski, et al., 2013; Strojecki, Colla, et al., 2013) and mineral materials (Verstrynge et al., 2009; He, Miao, and Feng 2010), signals with high-frequency content are associated with fracturing of the material structure, whereas signals with low-frequency characteristics (below 50 kHz) are typical of ambient noise.

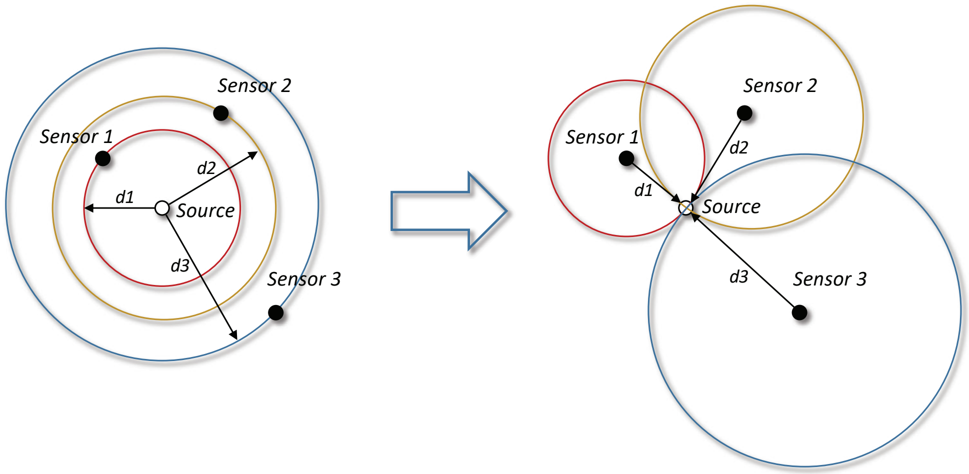
The further reduction of electrical noise and unwanted acoustic signals can be achieved by application of an anti-correlation measuring scheme. This scheme positions two identical AE sensors on the same object or different objects at a distance such that fracture events recorded by one sensor are out of range for the other. Environmental noise will impact both AE sensors simultaneously, and these specific events can be discarded by effectively filtering the data.

AE source location

Source location of AE events is a standard feature of multichannel measurement systems, and can be beneficial for understanding the damage process. Depending on the software and hardware setup, this technique can provide information about the exact location of the source event in the material or zone (area or volume) where fracture has occurred. The method consists of comparisons of AE signal arrival times at multiple AE sensors located in defined positions. Localization can be performed along a line (at least two sensors), in an area (at least three sensors), or in a volume (four or more sensors). Figure 17 illustrates the basic concept of localization of an AE event in a plane using three sensors.

Source location techniques assume that acoustic waves travel at a constant velocity within a material. When monitoring complex art objects, this may be a questionable assumption. The velocity of AE waves depends on sound frequency (multiple modes), and the density of the material. The presence of internal defects and geometrical boundaries can also complicate the analysis. Source localization techniques should therefore be limited to homogeneous materials (e.g., metals, stones) with relatively simple geometries and

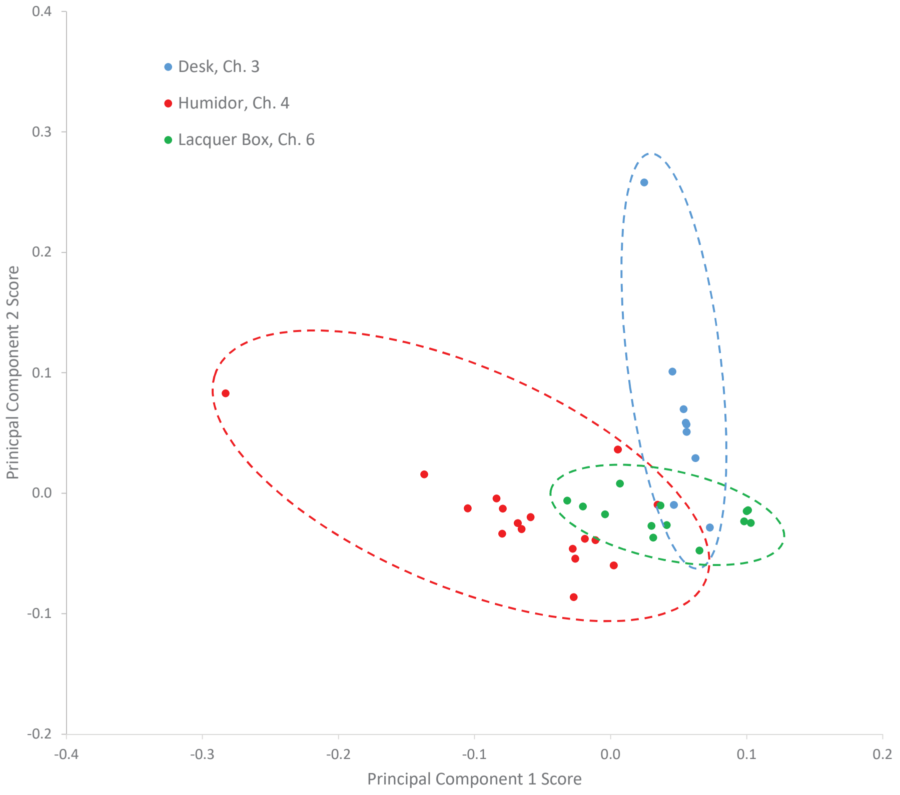
FIGURE 17
Localization of an AE event using the principle of triangulation. Three sensors define the source of AE in a 2D plane.



a small number of defects. For heterogeneous materials such as wood or multilayered structures, multichannel AE systems offer the possibility of monitoring different locations or objects and controlling noise using an anti-correlation technique, rather than allowing for AE source localization.

Frequency analysis

FIGURE 18
PCA analysis showing clustering of signals from three different monitored objects: wooden desk, wooden humidor, and lacquer-covered wooden box.



Acoustic emission hardware makes it possible to record the evolution of acoustic wave amplitude over time for each individual event, and frequency spectra can be acquired in real time. Since the duration of a typical emission burst is between 0.1 and 1 ms, several thousand spectra per second can be recorded by a sensor. A higher rate of AE signal is unlikely to be observed, except in the case of catastrophic macro-damage. The frequency distribution in measured spectra may suggest the underlying process from which the AE wave originated. Analytical techniques of pattern recognition may aid in distinguishing between fractures in different materials constituting a multilayered structure. An example of this type of technique, using principal components analysis (PCA), is shown in Figure 18: frequency spectra are measured during climate-induced micro fracturing of objects made with different materials and constructions, as recorded by KRNBB-PC sensors.

While the analytical method seems promising, complications may hinder its practical application. First, the measured frequency spectra depend on the sensitivity of the sensor itself, and differences between spectra diminish when narrow band sensors are used. The frequency characteristic of the signal is also attenuated with distance travelled within the material, and this attenuation may be greater than the initial differences between signals created during the fracturing of various test materials.

Although this method's potential for discriminating between signals associated with the damage of different materials is still not fully understood, it can be very effective for distinguishing electrical noise. Such signals have characteristic AC frequencies of 50 or 60 Hz, which can be easily recognized and discarded.

Automatic control of coupling

For long-term monitoring, and especially for early warning applications, it is of critical importance that AE sensors are properly connected to the monitored object. A compromised connection may result in an incorrect assessment of the fracturing process. A simple and straightforward method for checking the coupling of sensor to surface is to perform PLB tests in the proximity of the sensor, and compare results with previously performed tests. For applications where access to the object is difficult, or if particularly frequent or accurate evaluation of contact is necessary, automatic coupling control is an option. This technique consists of using a selected AE sensor as a temporary emitter of an ultrasound wave, which is then recorded by neighboring AE sensors. The process can be repeated at specified time intervals, and reductions in amplitude of the measured signal would indicate a worsening of the surface coupling for receiving sensors. A disadvantage of such an approach is that it requires the mounting of sensors in close proximity, which may not be optimal, and may limit the application of anti-correlation noise filtering.

6. Conclusions

AE is a highly sensitive analytical method that can be used to monitor the ongoing damage process in materials and objects. The technique's sensitivity makes it possible to predict macro-damage and accurately trace crack propagation in space and time. Furthermore, AE has allowed for the monitoring of micro-damage development in cultural heritage materials and objects. Application of an anti-correlation measurement scheme to reduce environmental noise allows AE to be employed as an early warning system, particularly when objects are subject to changing environmental conditions.

AE monitoring requires the use of advanced system hardware and complex data processing and interpretation. However, the expanding use of AE, particularly in cultural heritage, has initiated the development of standard measurement and data analysis protocols, increasing accessibility to the technique. A number of conservation science laboratories have incorporated AE as an analytical method to elucidate and quantify damage in artistic material. Museums have also shown increasing interest in AE due to its ability to support assessments of new, existing, and modified climate control strategies in the context of collection risk, with successful applications at the National Museum in Krakow (Poland), the Getty Museum (Los Angeles, USA), the Victoria & Albert Museum (London, UK), and the National Trust (UK). As the number of AE users in cultural heritage grows, it is important to connect with other practitioners, exchange experiences, and support the development of the user community, either through AEGIS (Acoustic Emission Group for Information Sharing, established at the Getty Conservation Institute) or a similar network.

Glossary

Absolute (true) energy
The squared voltage signal divided by resistance (i.e., $P = V^2/R$), and integrated over time. Energy units are typically given in attojoules (aJ) for AE events.

Amplitude
Peak signal during an AE event, typically given on a decibel scale (dB).

Average frequency
Counts above threshold divided by duration.

Counts
The number of times that the signal crosses the threshold during an AE event (hit).

Duration
Time period between the first and final threshold crossings.

Frequency centroid
The summation of magnitude multiplied by frequency, divided by the sum of magnitude over the power spectrum.

Hit
An AE event initiated by a signal larger than the user-defined threshold, and concluded when the waveform stays below the threshold.

MARSE energy
Relative energy determined as the measured area of the rectified signal envelope (MARSE).

Peak frequency
The frequency with the largest magnitude on the power spectrum.

Rise time
The time between the first threshold crossing (hit initiation), and the peak amplitude.

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Appendix

Program for Public Seminar at the Acoustic Emission Experts Meeting (November 2017)

Łukasz Bratasz (Jerzy Haber Institute, Polish Academy of Sciences, Poland)
‘Onset of Acoustic Emission in Conservation Science’

Marcin Strojecki (Jerzy Haber Institute, Polish Academy of Sciences, Poland)
‘Principles of AE, the technique and its application to monitoring of art objects in museums’

Nigel Blades (The National Trust, UK)
‘Acoustic emission monitoring to understand furniture response in a historic house environment, case study of Knole, England’

David Thickett (English Heritage, UK)
‘Of stones, bones, copper and glass’

Chiara Bartolin (Norwegian University of Science and Technology, Norway)
‘Preliminary exploration of AE for Scandinavian works of art’

Eric Hagan (Canadian Conservation Institute, Canada)
‘Applying acoustic emission analysis at CCI: an investigation of damage to sample wood structures during RH fluctuations in a climate simulator’

Michał Łukomski (Getty Conservation Institute, USA)
‘Acoustic emission in an epidemiological pilot study of a wooden object collection’

Roman Kozłowski (Jerzy Haber Institute, Polish Academy of Sciences, Poland)
‘AE as a tool to inform quantitative assessment of climate-induced damage risk’

Author Bios

Michał Łukomski is head of Preventive Conservation Research at the Getty Conservation Institute. He received his PhD in physics from the Jagiellonian University in Krakow, Poland, in 2003 and completed his postdoctorate fellowship at the University of Windsor in Canada. For the last several years, he has worked on describing quantitatively the response of hygroscopic materials relevant to collections of fine and decorative art, in particular wood, textiles, animal glue, gesso and paints to variations of climate conditions, using several scientific methods. His current area of research focuses on the mechanical characterization of historic materials, as well as nondestructive monitoring of damage development in art objects.

Łukasz Bratasz graduated in physics from the Jagiellonian University in Krakow, Poland, and received a PhD in 2002 from the same university. In 2002 he joined the staff of the Jerzy Haber Institute, Polish Academy of Sciences, Krakow. For many years he headed the Laboratory of Analysis and Non-Destructive Testing of Artefacts in the National Museum in Krakow and was also head of the Sustainable Conservation Lab at the Institute for the Preservation of Cultural Heritage, Yale University. Currently, he is associate professor at Jerzy Haber Institute. His research focuses on the degradation mechanisms of heritage objects due to interaction with the environment, risk assessment, sustainable preservation of heritage resources, energy efficient control of the environment in museums and historic buildings, and the impact of global climate change on cultural heritage.

Eric Hagan earned a master’s degree in mechanical engineering at Queen’s University in 2002, and went on to complete the Queen’s Master of Art Conservation Program in 2004. He then obtained a PhD in mechanical engineering at Imperial College London through a doctoral fellowship at Tate, which investigated the time-dependent tensile properties of artist paints under varied environmental conditions. Since completing his studies in 2009, he has worked at the Canadian Conservation Institute as Conservation Scientist. His role has involved delivering workshops on museum display cases and exhibition lighting, researching mechanical effects of the museum environment on objects, and also supporting Canadian heritage institutions through specialized conservation design projects.

Marcin Strojecki graduated in physics from the Jagiellonian University in Krakow, Poland in 2003, and received a PhD in 2009 from the same university. In the same year, he started to work in the Laboratory of Analysis and Nondestructive Testing of Artifacts in the National Museum in Krakow as a research specialist. In 2010 he joined the staff of the Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Krakow, where he is a research fellow. His research focuses on acoustic emission as a nondestructive method of diagnosing damage in historic materials.

Vincent Laudato Beltran is an assistant scientist at the Getty Conservation Institute. He holds a BS in general chemistry from the University of California, Los Angeles, and an MS in oceanography (geochemistry) from the University of Hawaii at Manoa. He joined GCI Science in 2002 and has been an active participant in a range of research projects including the mechanical characterization of historic materials, the effect of reduced oxygen environments on color change, evaluations of packing case performance during transport, and assessments of environmental management systems in hot and humid climates.

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