Preventive Conservation in Historic Houses and Palace Museums: Assessment Methodologies and Applications

SilvanaEditoriale

Preventive Conservation in Historic Houses and Palace Museums: Assessment Methodologies and Applications

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Using Science to Assess and Predict Object Response in Historic House Environments

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Abstract

Conservation assessment of objects is essential in historic house environments. Tight environmental conditions are not possible without very significant and often undesirable, alteration to the building fabric. Scientific techniques can support conservation assessment.

Periodic inspection techniques have been applied to furniture, ivory, and paintings. However, it can be very difficult to assign any damage observed, to particular environmental events. Continuous monitoring techniques can overcome this, with the effects of environmental fluctuations being obvious in the high frequency measurements.

The high cost or expertise required means these techniques will only be available in some instances. However, the results from these studies are ideal to develop damage functions to better assess other environments. Research has developed new damage functions and verified published functions. English Heritage collects data about all observed damage (and instrumental analysis) on its collections. This approach, although still developing, has proved extremely powerful to assess complex environments and develop evidence based risk assessments.

Keywords

Acoustic emission, digital image correlation, RH fluctuations.

Conservation assessment of objects is essential in historic house environments. Tight environmental conditions are not possible without very significant and often undesirable alteration to the building fabric. The recent CEN historic environment standard depends on conservation assessment to determine an object's stability or otherwise [BSI, 2010]. Scientific techniques can support conservation assessment and in some instances sensitive, portable instruments can detect damage before it is visible to the naked eye.

Attribution of damage cause is very common within conservation, both to improve environments where required and during auditing. Many deterioration phenomena look visually similar and scientific analysis can help differentiate in some situations. Analytical equipment is becoming more portable and less expensive, widening the situations in which it can be used. Additionally several pieces of non-invasive equipment are now available. This reduces the ethical issues with analysis, although most sampling for detecting or understanding deterioration can be balanced against greater future loss. Non-invasive techniques also allow replicate analysis to characterise the generally heterogeneous surfaces encountered and multiple measurements on the same spot at different times, from which deterioration rates can be derived [Thickett *et al.*, 2017].

Science has been used to develop criteria-anchored systems to visually describe mould growth and culture and molecular methods to identify the species present and risk. It is beginning to be used more widely to track chemical deterioration. The identification of corrosion products often indicates the source of corrosion. The quantification of soluble salts in stone and ceramic, combined with thermodynamic modelled yield least damaging temperature and RH ranges to minimise future damage. The state of conservation of paper, leather and enamels can be determined. However this paper will focus on physical deterioration, primarily caused by RH fluctuations. This is not a review paper and although examples will be presented, they are chosen to explore certain points and not as a comprehensive review of the field

Every instance of potential environmental damage across English Heritage's collections is investigated. The prime driver for this is our approach to standards based on the previous behaviour of the collections, conservation science and the rooms control capacity [Thickett *et al.*, 2012]. Hence knowledge of adverse behaviour is essential. A minimum data: including the date the damage was observed; the estimated date when the damage was last observed to not be present; two images (a general one of the object and a close up of the damage) are collected and a years worth of environmental data from the room the object is in. Extra monitors are often put out to determine the relationship between the room sensor and the object environment. Further environmental analysis is frequently undertaken for diagnostic purposes. The damage may be further investigated analytically, with corrosion products, salts or mould species identified.

The accuracy of audit data is often questioned. Methods are available to assess and improve inter-surveyor bias [Taylor, 2017]. The other major source of error is sampling error, as collection sizes and resources often preclude full audits. Data from five existing full audits was resampled digitally to assess this error. The sampling method was that used in English Heritages audit methodology [Xavier-Rowe, 2011]. The results were assessed in terms of the percentage of unstable (category 3 and 4) objects and compared to the value for the full audit set. The digital resampling was undertaken 100 times for a 5% sample. The distribution of data was tested for normality using the Shapiro-Wilk test with alpha value of 0.05, and found to be normally distributed [Shapiro

Material/location	**Full audit percentage unstable**	**Mean of 5% audit**	**Standard deviation**
Archaeological iron, whole EH estate on display	2.56	2.53	0.83
Paintings, whole EH estate on display	2.24	2.29	1.12
Gilded furniture, whole EH estate on display	1.98	1.94	0.98
Wide range of fine and decorative arts objects at Audley End House	1.70	1.81	1.26
Wide range of fine and decorative arts objects at Apsley House	2.87	2.98	1.34

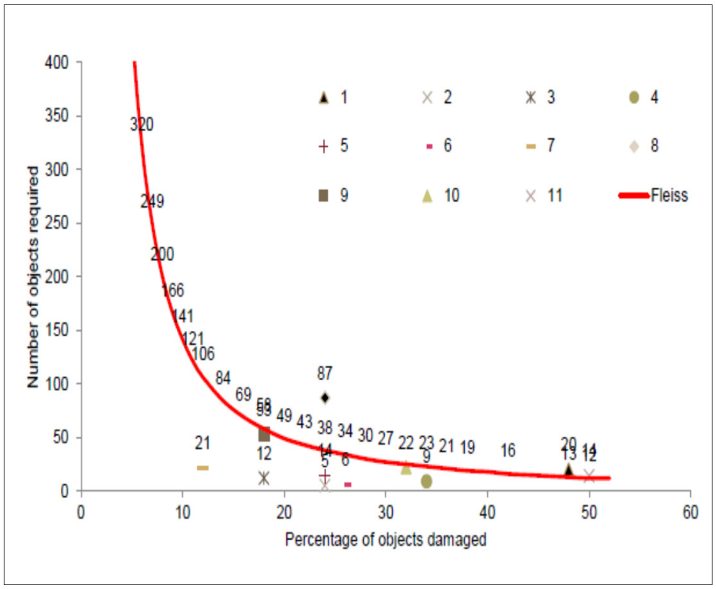
Table 1
Results of digitally resampling full audits at 5%, 100 times.

and Wilk, 1965]. Hence the standard deviation was calculated. Results are shown in table 1.

As can be seen, at 95% confidence interval (2 standard deviations), the data from the single material type audits has a narrower distribution. Auditing a mixed collection increases the sampling errors. This is quite likely due to an increase in the variation of the objects.

One use of audit data could be to try and relate object response to environment in the spaces audited. The number of objects required to provide statistically significant results is important for this approach. Display rooms will generally have more aggressive environments, as they are much more difficult to control in rooms open to the public than generally closed stores. Unfortunately, the number of objects present limits the potential sample size. Most historic rooms have slightly or very different environments from each other. The number of a particular object type is often limited in a room. The epidemiological field has developed statistics to determine the number of objects required to form a significant study at different damage rates in the two groups [Fleiss *et al.*, 2003]. Results from this work (using alpha and p value of 0.05, essentially meaning there is a 1 in 20 chance that the two comparison groups do not represent the whole population from which they are drawn) are shown in figure 1. Assuming one group is in non-damaging conditions, then the difference in damage rate, expressed as a percentage of objects damaged forms the x axis (if the second group has been damaged by the conditions the difference is lower). As can be seen object numbers required for each group increase dramatically as the damage rate (difference) decreases. The damage database gives the number of damaged objects of a particular type in a room, when combined with a count of all object of that type, the different in damage

Fig. 1
Number of objects required for a statistically robust comparison of two groups of objects.



rates can be assessed. A small set of results are plotted on figure 1. The numbers are also marked on figure 1 for ease of comprehension.

As can be seen, well over half of the instances shown did not have enough objects present at the damage level measured to provide statistically robust information. Careful selection is required for rooms and collections for studies using such an approach. One advantage of using sensitive analytical techniques, is as the difference in condition that can be detected, can be much smaller than by visual examination. This reduces the number of objects required for robust statistics. This number can frequently be limiting as shown.

Periodic Measurements

A range of inspection techniques have been applied to collections. These include commonly: photography and crack measurement, visually, with gauges or with measuring microscope. Photogrametry, 3D laser scanning, electronic speckle interferometry and digital image correlation have also been applied in a few instances [Dulieu-Barton *et al.*, 2005]. Measurements are sometimes applied periodically. Most reported instances have been of just two sets of measurements, with an attempt to link changes to the environment experienced.

In Situ Digital Image Correlation (DIC) Development

In order to deploy DIC in situ, some aspects must be taken into account that differ between a laboratory and the context of a historical building. DIC is an imaging technique that can be very sensitive, able to measure sub-pixel movement. This technique is based on comparing images over time, extracting a displacement map over the image

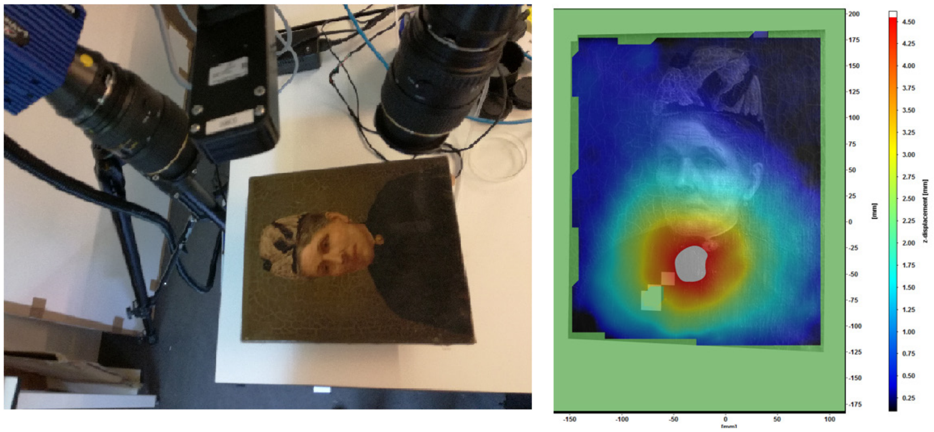


Fig. 2
DIC setup observing a canvas painting (left), out-of-plan displacement map (right).

that can highlight deformations and defects. In many cases, computer vision cameras will be used, these have larger sensor of higher quality producing less noise than commercial ones. However, their price and required handling limit their accessibility. Additionally, as micro-meter displacement are being measured, the experiment needs to be conducted in a very stable environment with low vibration. This is generally not the situation that we encounter in historic buildings.

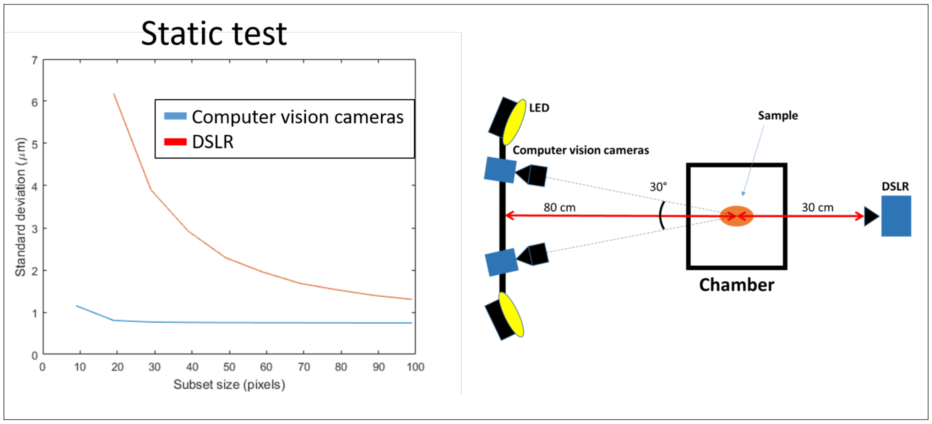
The main feature that can complicate a DIC measurement of artworks is the image's pattern. It is required to have random features on the observed surface. Industrially, a pattern is usually applied onto the tested material. This cannot be done on many artworks, as we wish to have no interaction with the object and only rely on the imaging over time.

The restriction on pattern application is not limited to cultural heritage. Studies looking at damage under water (where the pattern may dissolve), rely on the natural pattern of the material. The same approach can be applied on many artworks where aesthetic details, cracks, brush strokes, can form random features. But this excludes objects that have featureless surfaces or large areas in plain colours. Additionally some artworks include both, such as a portrait with many details on the character and a plain dark background. These limitations require a thorough assessment of the pattern before any measurement is considered.

Initial tests applying a small displacement at the back of a portrait allowed the displacement to be located and measured (fig. 2, right). The rather plain background was not an issue as its surface was uneven, limiting dead points only to reflection of light, changing the pattern. But this particular experiment, despite being able to measure displacement without applying any pattern, resulted from a significant movement of the painting compared to the sensitivity of the instrument.

Further tests show that change in RH and moisture absorption can

Fig. 3
Comparison between the computer vision setup and a single DSLR.



also be detected on a painting. However, they were done in a controlled environment. The question remains regarding how much of the data can be trusted and how the environmental changes, such as the light intensity, will impact the results. By moving the painting during the previous test, the light reflection on the varnish changed the pattern observed by the camera creating dead points. We can easily expect such errors from a measurement in situ alongside vibrations.

Before deploying a camera on site, it is crucial to make the instrument accessible to an heritage institution and suitable for stand-alone experiments. To do so, we compare results of standard sample with a random speckle between a full computer vision setup and a single commercial camera as shown in figure 3. The graph shows the random error versus the displacement map resolution. Whilst this data is not sufficient to give the absolute accuracy of the system, it is crucial to assess how the cameras are seeing the patterns over time. This will fluctuate, creating virtual displacement. Even though the computer vision cameras have significantly less noise despite being further away, the DSLR had a very reasonable error level up to 6μm which is promising.

With this in mind, we can start to monitor real painting on site, starting by assessing their pattern and the impact of the environment on it. In the best case scenario, the object should move by a well defined distance which will be compared with the displacement measured through DIC. In practice, it is not possible to move the painting or the camera, on site down to the micrometer precision. Therefore we started to consider the random error as featured in figure A2. Several paintings from the Wellington Collection at Apsley House (English Heritage) were considered. Overall, the landscapes worked better since they include more details on both foreground and background. The portraits were more complicated with often a plain background and homogeneous regions on the foreground (cloth, part of the face, etc.). The random error measurement gave good results for most of

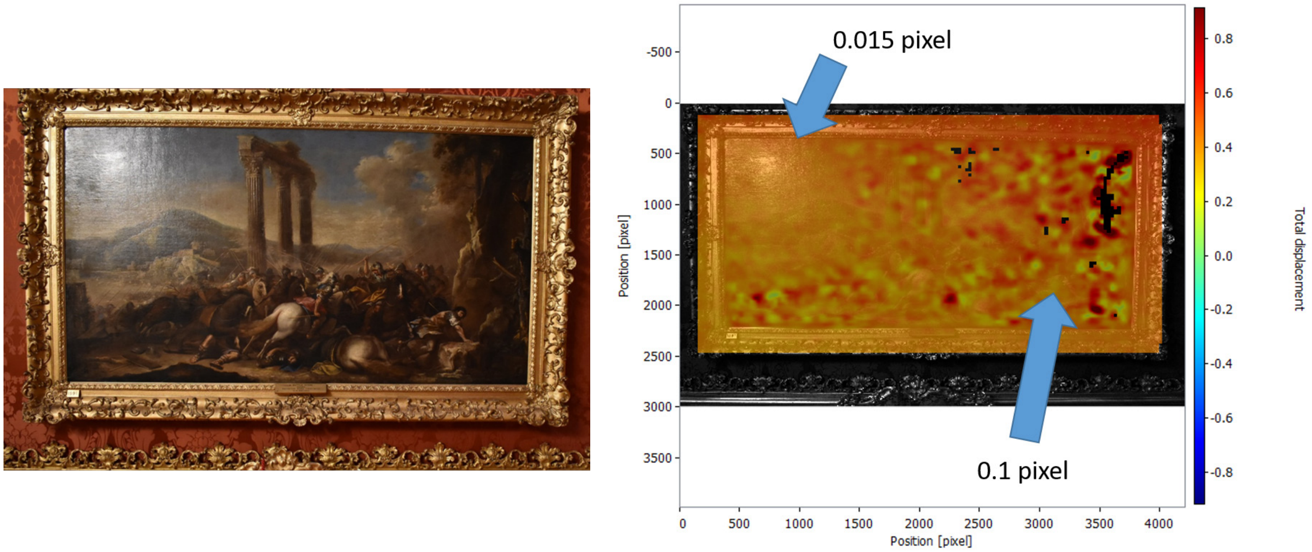


Fig. 4
Random error measured of a painting.

the painting observed. It demonstrates the potential feasibility of long term monitoring of the painting, if changes due to RH are significant enough to be detected. However, reflection of light strongly impacted the noise measurement as shown in figure 4.

The reflection on the varnish in the top left corner, enhanced the canvas pattern through the painting layer giving more defined random features in this area. However, the ambient light can affect this pattern, shifting the error and this can be confused with real movements by the camera. This could be solved by carefully controlling the lighting. Hence we should continue this research to evaluate how such error can be accounted for during the data analysis.

Indirect Tracing

For physical damage, generally associated with RH fluctuations, periodic measurements have the major drawback in that unless a quite extreme event occurs it is difficult to assign the damage to a particular fluctuation, or combination of fluctuation and previous conditions. The measurement intervals are often long and the environment in historic buildings, frequently changes. Continuous measurements can allow the linking of response to particular episodes or exploration of this. The terminology “tracing” has been used by some researchers. A selection of methods is shown in table 2. Some of these methods have been applied to long term monitoring of objects in situ, others have the potential for such application, but the authors have not seen any reported instances.

With the exception of mass and moisture content all the methods listed in table 2 require firm attachment to the object surface, which can

Technique	**Applied to**	**Issues**	**Reference**
Strain gauges	Wood	Requires very flat surface, temperature dependence	
Linear voltage differential transducer	Cracks in furniture and panel paintings		Knight and Thickett, 2007
Bragg fibre	Panel paintings, tapestries	Fibre stiffness can affect object response	Dulieu-Barton et al., 2005
Deformetric kit	Panel paintings	Need space behind the panel	Uzielli *et al.*, 2012
Mass	Furniture, sculpture, ivories		Thickett et al., 2006
Moisture content	Furniture		Thickett, not published

Table 2
Continuous measuring techniques.

be problematical. All of the methods are indirect, in that they measure a property of interest such as length, but not damage. Interpretation of the data is required to infer a damaging event, which requires a deep understanding of the mechanical properties of the object being measured. This is problematic, as mechanical testing, which is destructive, requires significant sample sizes and most data is only available for modern and not aged materials.

Direct Tracing

A more direct method is acoustic emission. Small sensors detect high frequency vibrations when rigid materials undergo micro cracking on deformation [Strojecki *et al.*, 2014]. The sensors can be pushed against the object without attachment. The scale of damage detected is very significantly below what can be seen by visual inspection. The technique has been used for enamels, stone, metals and wood in cultural heritage. Wood is amongst the most difficult materials to measure, with rapid attenuation of the signal, moisture affects and large differences in response due to growth directions [Kawamoto and Williams, 2002]. The signals from wood are relatively weak and background noise is a major limitation in a location. This determines the practical detection limit. The noise originates from two sources; electromagnetic and physical activity [Diodati *et al.*, 2001]. Differential sensors are the least sensitive to electromagnetic noise of those available. There is a general background level of noise, normally removed by a setting a threshold value below which signals are not recorded. Additionally, there are periodic noise events of a similar magnitude to those from micro-cracking in wood. Some are correlated with the shock, visitor movement induces in objects, either directly or through vibration of (especially) wooden floors. The use of two sensors in anti-correlation mode is used to avoid recording such events. The two sensors are placed far enough apart (generally over 6 cm) to not respond to the same event in the wood. Events are only recorded that occur on just one sensor, assuming an

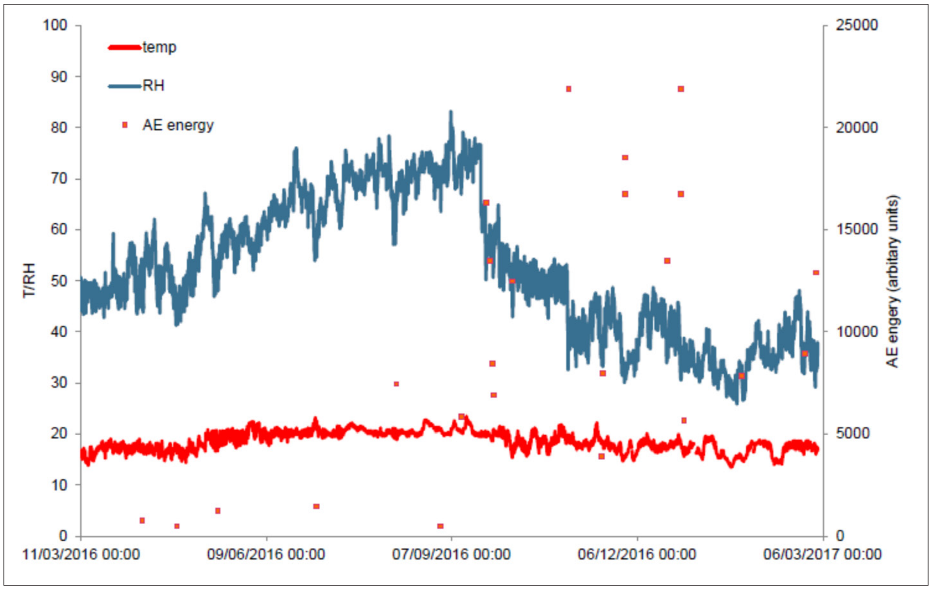


Fig. 5
Acoustic emission and climate measured from and around mahogany chest.

event recorded on both sensors is noise. The most common application has been to monitor crack extension by placing a sensor on a crack tip. An 18th century walnut veneered pine chest was monitored at Walmer Castle. A physical acoustics PAC 125 system was used with two WD sensors in anti-correlation mode. The use of preamplifiers allowed the equipment to be placed some distance (5 m) away from the chest so as not to visually disturb the historic interior. The provision of electricity sockets is also often very limited in historic buildings. Shock monitoring was undertaken at the same time with MSR 145 tri-axial loggers.

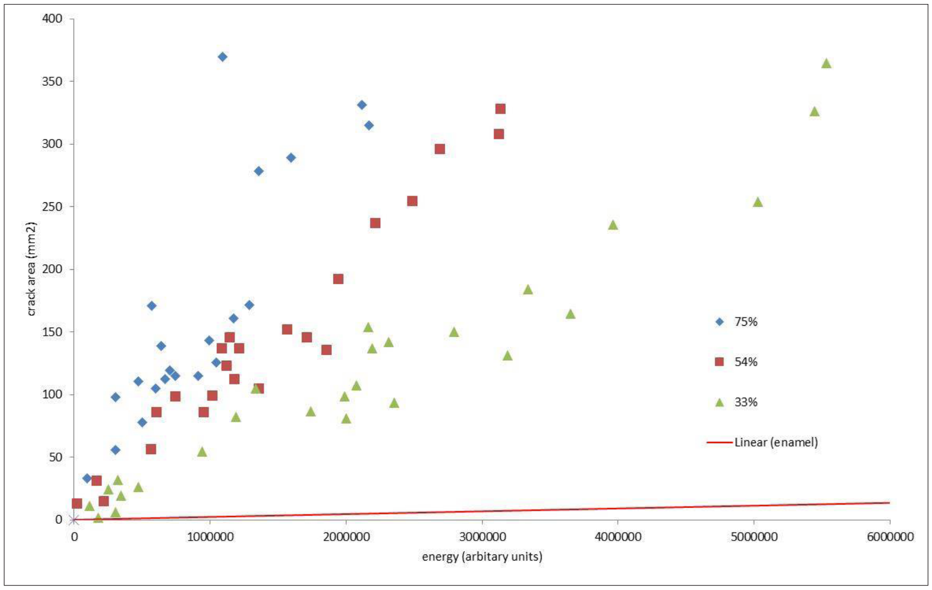
Results of a year's monitoring are shown in figure 5. Any events coincident (within a second) of shock event over 0.1 g were excluded.

There are a number of acoustic emission events throughout the year. The most intense, highest integrated energy events appear at dryer periods. Full discussion of the results is beyond the scope of this paper and will be discussed with a corpus of similar monitoring in a future publication. The very high temporal resolution allows analysis of correlation with environmental data. The acoustic emission events are recorded over a fraction of a second and can be correlated with shock events, to remove this source of noise.

A series of calibrations were undertaken with 1 mm walnut strips equilibrated to 75, 54 and 33% RH. These were pre-notched (1 mm by 2 mm) and pulled apart in an Instron tensile tester. The crack area increase on crack length extension was correlated with the amount of acoustic emission measured. Each calibration was carried out with 5 samples. Calibrations are shown in figure 6 along with one for enamels.

There is a significant difference in acoustic emission response to the

Fig. 6
Calibration of acoustic emission energy generated by crack growth at different RH values.



same crack extension at different RH values due to the different moisture contents of the walnut. All the wood responses are very significantly less than the enamel. Only the low extension part of the enamel response is shown. The calibration, using optical determination of the crack length has a low sensitivity (measurement interval of 0.2 mm), which means the calibration curve is mainly above the level of acoustic emission detected on objects.

These calibrations were applied to signals generated within 24 hours of >63%, 44-64% and <44% to produce figure 7.

With the different acoustic response of the wood at different RHs taken into account, the distribution of the amount of cracking changes and the drop from 75 to 50% now appears to be the most damaging. There is a drawback with this approach. It gives more readily accessible and understandable results, but relies on calibrations with modern wood, and hence becomes a less direct method. Further research is required to determine if the acoustic response is the same for modern and aged wood.

Damage Functions

With a few exceptions, the high cost or expertise required means these techniques will only be available in some instances. However, the results from these studies are ideal to develop damage functions to better assess other environmental data.

The environments in historic buildings are generally complex. It is often difficult to translate the results of laboratory experiments for these environments. This has led to a situation where we have a good understanding of safe limits (where there is absolutely no risk

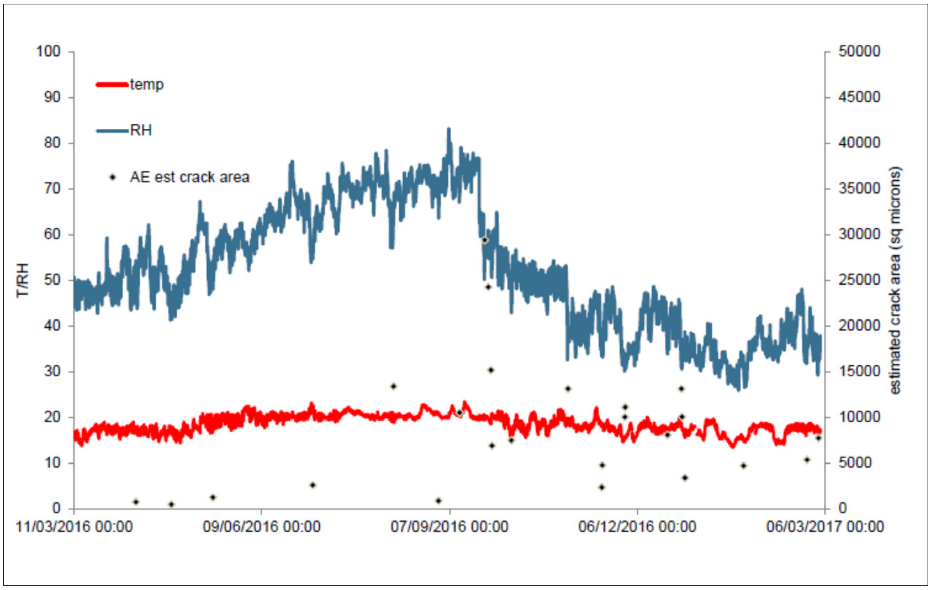


Fig. 7
Acoustic emission data from fig. 5, recalibrated to compensate for RH.

to objects), but next to no comprehension of how much risk there is when we move beyond these limits. These safe limits are impossible to maintain within the vast majority of historic buildings. A promising approach to determine risk, is the use of numerical damage functions. The response of a large group of objects is measured and mathematically correlated with the RH conditions. This mathematical function can then be used to assess other environmental RH data to give an indication of the risk. This approach has already been elaborated to some extent in several instances shown in table 3.

This approach is also helpful for processes such as corrosion that depends on both concentrations of pollutant gases and RH, and sometimes, temperature [Thickett, forthcoming].

The database of observed damage has been very useful to test and calibrate these damage functions. Work has been undertaken investigating and comparing mould outbreaks, indicating a better correlation with two of the four published damage functions to instances observed across English Heritage's estate [Thickett *et al.*, 2014]. Work is planned in the near future to investigate instances of physical damage. This approach, although still developing, has proved extremely powerful to assess complex environments and develop evidence based risk assessments.

Conclusions

Scientific methods can aid in determining object response in some instances. There are significant restrictions with their use on historic objects, but many examples where these have been successfully overcome. One major advantage is enhanced sensitivity, which has been

Function	**Notes**	**Reference**
HERIe	Finite element analysis	Heri-e
BS EN 15757	Mathematical method based on experience	BSI, 2010
Variety of methods developed into damage functions		Lankester, 2013
Data analysis at different fluctuation periods		Pretzel, 2014
Mould on wood	Four published functions based on laboratory experiments	Thickett *et al.*, 2014

Table 3
Damage functions.

shown to be particularly important for the statistical comparison of response to environments.

Digital image correlation can be used with more conventional cameras, making it accessible to heritage institutions, and long term monitoring as it can be easily battery powered. The natural pattern of canvas painting does work in many cases, but not all painting can be observed, in particular those lacking features. Even though movement can be monitored, the sensitivity of the technique will depend on the painting, due to the pattern quality. Ambient RH fluctuations might be too small to be detected for some, whilst easily measured for others.

Acoustic emission has been shown to be particularly useful, and the limits of detection due to noise levels assessed.

Developing results into damage functions is an area with very significant future potential. This may lead to great improvements in assessing environmental data.

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Palace of Versailles.
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