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Integrating non-destructive techniques into the scientifically robust assessment of vulnerable historic masonry. Case studies on Reigate Stone at the Tower of London

Received (in revised form): 7th June, 2021

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Abstract

This paper summarises a scientific methodology for assessing masonry decay, developed over the course of a four-year research project on Reigate Stone at the Tower of London and Hampton Court Palace. Reigate Stone is a vulnerable building stone with a complex history of use, high cultural value and poorly understood decay processes. The Tower of London and Hampton Court Palace, managed by Historic Royal Palaces, contain a large amount of Reigate Stone masonry. As such, these important historic sites provided a range of different case studies for investigating Reigate Stone decay. Masonry decay is increasingly being understood in terms of complex system dynamics, in which the interactions between primary building stone, replacement stones, mortar and invasive agents of anthropogenic or environmental origin are as important as the nature of the building stones themselves in controlling non-linear response to environmental mechanisms. Integrating this diverse set of variables significantly increases the complexity of scientifically robust stone conservation. Non-destructive techniques (NDT) play an important role in addressing this complexity, but in order to make sense of the data they capture, it is vital to appreciate different scales of investigation and distinguish between rapid and in-depth protocols.

Keywords: heritage, historic building survey, stone decay, non-destructive techniques (NDT), conservation, moisture meter

INTRODUCTION

A robust approach to understanding the causes of masonry decay will become increasingly necessary in response to mounting pressures on the management of large historic sites. As rapid climate change begins to alter the processes of decay, diagnostic methodology will need to be able to interpret the effects of

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Journal of Building Survey, Appraisal & Valuation
Vol. 10, No. 3, 2021, pp. 1–15

2046–9594

new rainfall and pollution patterns. Beyond climatic factors, the COVID-19 pandemic has revealed the vulnerability of the complex economic systems underpinning the management of cultural heritage. Shocks to fiscal and human resources, including the premature retirement of knowledgeable, veteran personnel, risk a devastating impact to architectural conservation protocols. It will be necessary to identify controls and implement targeted conservation strategies within short timeframes in order to mitigate the scale of change seen in previous eras of rapid environmental and societal upheaval. Non-destructive techniques (NDT) have become an established part of the historic building surveyor's repertoire and provide an important link between more traditional surveying techniques based on experience and controlled experiments. They play a vital role in any scientific approach to understanding masonry decay, provided their limitations are accounted for.

Reigate Stone is a good example of what the field of stone conservation until recently referred to as a problem stone.[1] Used extensively in Medieval London and south-east England, it was arguably the region's principal freestone between the 11th and 16th centuries. Neither a limestone nor a sandstone in the true sense, it has an unusual, highly porous silicate matrix and varying amounts of calcite and clay. In some scenarios the stone decayed rapidly, which led to declining use and wide-scale replacement between the 16th and 20th centuries. Mined from the Upper Greensand in north-west Surrey, the stone had industrial uses that lasted beyond its use in architecture, but the last mines closed in the 1960s.[2] Past conservation strategies have often been ineffective and in some cases appear to have accelerated decay; however, some stones have survived remarkably well (see Figure 1). Given the extent to which the stone was exploited, its unusual mineralogy with several variations, the environmental stresses of industrialising London and the dynamics of past construction and repair, it has been difficult to ascertain the relative influence of environmental mechanisms and material properties in decay processes. This makes the selection of appropriate conservation strategies difficult. In many cases, vulnerable stones like Reigate Stone represent important chapters of regional built heritage, during which only limited typologies of building stone were available and prior to significant environmental and societal changes. Therefore, they often have great cultural value. Given their increased risk of deterioration, safeguarding the information stored in these stones for future generations is both particularly important and particularly challenging.

Between 2016 and 2020, an extended research project on Reigate Stone took place within the framework of the Centre for Doctoral Training in Science and Engineering in Arts, Heritage and Archaeology (SEAHA), an Engineering and Physical Sciences Research Council funded programme which responded to the need to train interdisciplinary scientists and engineers in cultural heritage studies. Historic Royal Palaces (HRP) initiated the project to build on previous research they had conducted on Reigate Stone. They part-funded, provided site access and supervisory support to the project, which was based at the Oxford Resilient Buildings and Landscapes Lab (OxRBL) in the University of Oxford's School of Geography and the Environment. The conservation architects Carden & Godfrey Architects, who have built up a portfolio of work at the Tower of London, provided additional supervisory support. The project further benefitted from an interdisciplinary advisory board, made up of architects, surveyors, conservators, and scientists.

The overall aim of this project was to facilitate the development of sustainable conservation strategies for Reigate Stone. Developing sustainable conservation

Figure 1: Two primary Reigate Stone ashlar blocks in the lowest, east-facing course of the White Tower, Tower of London
Source: Author

strategies requires a scientific understanding of the mechanisms driving decay, the impact of decay processes upon the stone, and the corresponding effects in the wider context of historic masonry and built heritage. This detailed understanding can be used to identify controls within the complex system dynamics that govern change in the historic built environment. The specific research objectives were: a) to better understand the composition of Reigate Stone masonry, including lithological variations, historical developments, common contaminations and decay patterns; b) to assess past and present conservation strategies; and c) to characterise decay and link processes to measurable environmental mechanisms. This was achieved by developing an integrated methodology, which defined a clear scientific framework and then used different experimental methods at different scales to build up a picture of the complex system dynamics. This paper summarises that methodology, with a particular focus on NDT and transferable knowledge that could be useful to the field of historic building surveying.

MAKING SENSE OF REIGATE STONE DECAY

In order to better comprehend the dynamics of Reigate Stone decay, the controls of building stone decay were conceptualised along three axes of variability.

(1) Material variability within the stones used in construction. Stones can be harder or softer, more or less porous, more or less

homogeneous, etc. As a result, their baseline resistance to decay processes will differ. Given equal environmental mechanisms, and equal histories of use and repair, they will decay at different rates and according to different patterns. In Reigate Stone, mineralogical variability can be expressed according to the relative content of three different cementing components: opal-CT forms a weakly cemented porous matrix, clay minerals include hygroscopic swelling clays, and calcite improves strength;[3]

(2) Environmental variability within the current and recent exposure of historic masonry. Stones can be completely sheltered, highly exposed and everything in between. The same stone, with the same history of use and repair, will follow different decay pathways in different locations;

(3) Historical variability. Alterations to the material characteristics of the stone or its surrounding masonry, or to the environment it is exposed to, will have resulted in diverse contingencies, or 'case histories'. For example, initially comparable stones found in similar present-day environments may display very different decay features due to treatment with different consolidants. Fully integrating this axis into a systematic understanding of the historic built environment is particularly challenging, as it is also manifest in changing attitudes to deterioration across time. This establishes a complex reciprocity between decay process and remediation.

The Tower of London provides a suitable location for a case study of Reigate Stone due to a relatively large stock of primary masonry. Construction started with the Norman conquest of 1066 and continued through three major phases of expansion into the 14th century. This marks the period in which Reigate Stone use became widespread. First use of Reigate Stone was as ashlar in the lower part of the White Tower[4] (see Figure 1), and it can be found throughout the site. Later medieval or early Victorian repairs are likely. Mineralogical variations are highly probable due to changes in quarry provenance across these centuries. Owing to the importance of the site, treatment history and past changes in local environment are relatively well documented. A diverse present-day setting, which includes masonry facing all aspects, sheltered, and indoor examples in rooms of varying use, adds variation to the type of environmental mechanisms that can be expected to drive decay. As a world heritage site with over 2m visitors a year, the site can also provide useful information on the general usability of new surveying methodologies.

SCIENTIFIC METHODOLOGIES FOR THE HISTORIC BUILT ENVIRONMENT

To enable an assessment of Reigate Stone deterioration along the three axes of variability, a transdisciplinary, multi-method approach was adopted for the research. Field surveys occupied the central part of this approach; however, the research methodology also combined archival and documentary analysis, laboratory experimentation and numerical simulation. Field investigations implemented a wide range of portable NDT used in combination with monitoring techniques to define and establish the pattern and variety of Reigate Stone conditions. This was primarily used to investigate the effect of environmental variability and different historic treatments, while also enabling material calibrations necessary for making sense of controlled experiments. Laboratory experimentation focused on determining the response of Reigate Stone typologies to controlled environmental mechanisms. Documentary analysis of extensive grey literature, within HRP archives and elsewhere, provided evidence of provenance, construction, treatment, and other changes to Reigate Stone masonry environments. As shown in Figure 2, aspects of each of these dominated the specific projects within the overall thesis, which each attempted to examine variability across one or two of the defined axes.

Underpinning the methodology was a progressively detailed series of site surveys at the Tower of London and Hampton Court Palace, two of the major sites with significant amounts of extant Reigate Stone. This approach used increasingly detailed survey methods to gradually focus a large area of investigation into representative scenarios. Initial surveys mapped general spatial patterns and defined notable conditions across the sites; rapid NDT were used to assign qualities and basic characteristics to these observations in the most representative locations; ongoing surveys utilised progressively more time-intensive methods to link the characteristics and measurable properties deemed significant to specific research questions. This method formed the fulcrum for controlled experiments, which were designed to address questions uncovered during the field surveys. Any destructive testing or sampling was performed after several stages of this surveying methodology had identified locations of high scientific but low cultural impact.

These surveys facilitated the gradual identification and investigation of representative

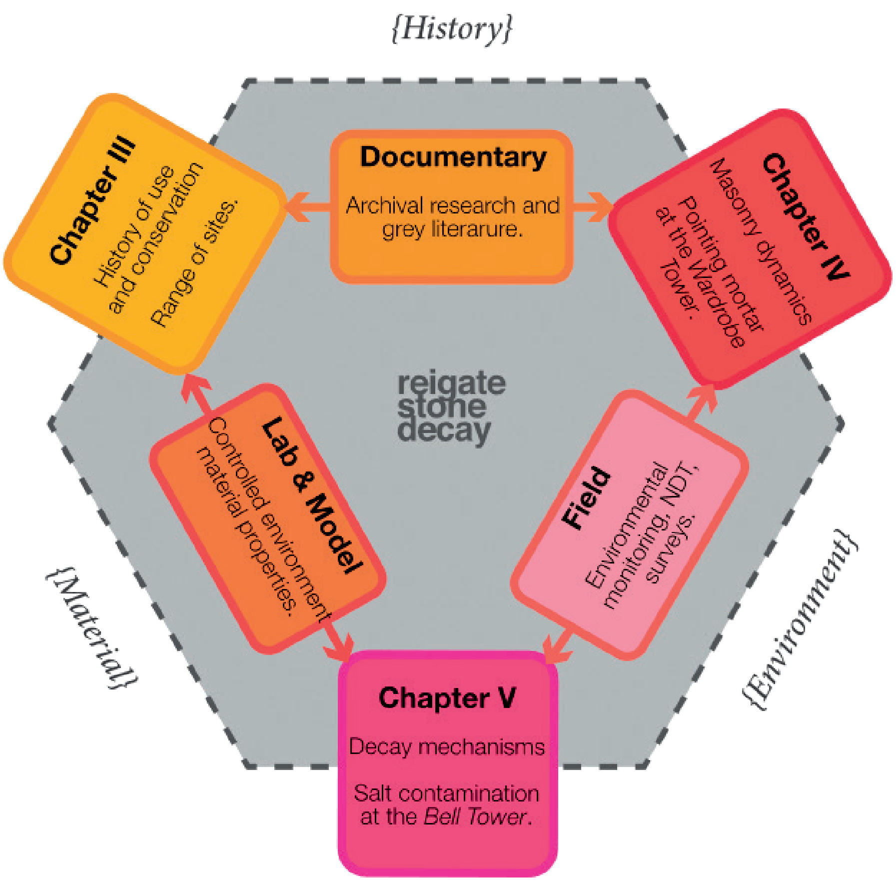

Figure 2: Diagram showing ‘variables’ of Reigate Stone decay, related methods of investigation, and individual research projects of doctoral thesis

Source: Author

sites and samples. Aided by archival research to ascertain areas of Reigate Stone masonry with suitably rich documentation, this centred on two buildings at the Tower of London.[5] The Wardrobe Tower, a highly exposed ruin with 12th-century Reigate Stone ashlar in advanced stages of decay, which was repointed with lime putty mortar in 2017 (near the beginning of the research).[6] The Bell Tower, also containing 12th-century masonry, but with a more varied environment and several mineralogical types of Reigate Stone showing different decay patterns. Additional fieldwork was done at Hampton Court Palace, and on a test wall built at the Tower in 2001 to assess the long-term impact of a novel consolidant on Reigate Stone. Besides the range of environments and 'case histories', this broad approach integrated a diverse documentary history into the research.

The HRP archives include treatment reports, condition surveys and historical photos of the Tower and Hampton Court Palace, as well as a vast library of anecdotal observations in notes and communications stretching back to the mid-1990s. This material formed a key resource in understanding recent developments and selecting suitable sites for investigation. Material prior to this period is sparse due to changes in management; the National Archives provide a further repository going back centuries. This was used in a targeted manner once key sites had been selected and research questions more precisely defined. HRP employ clear metadata standards for the naming of files and description of photos. These are being observed, as data gathered during this project is archived for posterity.

USING NDT WITHIN A COMBINED METHODOLOGY

Given the cultural context of stone conservation and prevailing heritage values, a crucial factor of any methodological framework is to minimise intervention in the historic fabric. Extracting material samples from historic sites is generally limited and monitoring systems need to be inobtrusive. Given the high variability of the historic built environment, this poses challenges to effective fieldwork. NDT provide a vital opportunity for the in-situ examination of historic fabric. The term refers to a wide range of techniques that can be used to examine materials without the need for sampling; however, great care must be taken when defining the context and scale of investigation. While individual measurements in localised areas can provide useful data, the variability of the historic built environment means extrapolating a diagnosis from individual areas or even individual devices is rarely possible.[7]

Distinguishing between rapid and in-depth NDT surveys can be a useful first step to producing meaningful datasets.

- Rapid surveys can be used to investigate the need for further surveys or support broad conceptual arguments. In these cases, small datasets based on small numbers of readings can suffice. Calibrating or triangulating measurements is not always necessary; the NDT is used to highlight spatial or temporal conditions;
- In-depth surveys can be used to gather empirical data, linked to specific material properties. This demands a more rigorous and robust approach, which contextualises spatial or temporal conditions into patterns of response. It can benefit from combining two or more NDTs in order to triangulate results and may require further calibration with laboratory tests in order to account for case specifics.

The distinguishing factor of these approaches is the extent to which they focus on resolving environmental or spatial (ie material) scale. The rapid approach can resolve a moment in time or a point in space. Given the variability of the historic built environment, this will rarely be sufficient to facilitate a meaningful diagnosis. Nevertheless, in the hands of an experienced operator it can be the first step to identifying areas of interest and either designing in-depth surveys or developing research questions for experiments in a controlled environment. In-depth surveys can work across longer timescales and/or larger areas to assess changes to and interactions within a defined system. This could involve the repeated application of a rapid protocol using a suitable NDT at one location. Alternatively, it could make use of complementary NDT, for example two instruments that provide a different measurement of moisture content, to increase confidence in the findings. While a rapid survey can involve a relatively standardised protocol, an in-depth survey will require a specialised protocol developed according to the demands of the building or site.

The following sections will outline three NDT protocols, which were developed to assess different aspects of Reigate Stone masonry decay. A long-term, high spatial resolution, non-destructive survey using two complementary techniques was performed to combine environmental and material testing at the Wardrobe Tower. This aimed to investigate the role of pointing mortar in the moisture dynamics of highly exposed, vulnerable masonry. A rapid material analysis of Reigate Stone surfaces was developed to assess historic treatments at several locations across the Tower of London and Hampton Court Palace. A long-term environmental monitoring with targeted material testing was used to investigate differential decay patterns at the Bell Tower. Using the same NDT across these surveys and in parallel laboratory tests increased confidence in the interpretation of results and enabled synergism of datasets. This broadened the overall findings on the general theme of Reigate Stone decay, while still tackling three specific research questions.

LONG-TERM NDT PROTOCOL FOR OBSERVING MULTI-SCALE MOISTURE DYNAMICS

At the Wardrobe Tower, a surface rebound hammer (Equotip, Proceq) (see Figure 3) and moisture meters (T660, Trotec and CEM, Shenzhen Everbest) were used to assess the moisture regulation of Reigate Stone masonry over a two-year period following conservation work in 2017.[8] The objective was to establish the role of pointing mortar type, by comparing the soft lime putty mortar (current best practice) and a test area of natural hydraulic lime mortar (NHL) used in the 2017 work, with older, cementitious mortars dating to the 19th and 20th centuries. Effective pointing mortar aids moisture regulation by drawing moisture out of the edge of a stone block through the mortar joint. There were five survey campaigns across the two-year period. The investigation combined the use of the NDT with more traditional, visual assessment techniques. This combination enabled a multi-scale evaluation of the masonry system, which assessed both localised and structure-wide moisture dynamics in response to different environmental conditions. There was further evidence to support the common understanding that lime putty performs better than new NHL mortar, which was shown to trap moisture at the interface between stone and mortar. Older mortars used in 20th-century conservation work also regulated moisture well, however, despite their cementitious binders. This suggested that mortars with initially inappropriate recipes can age sympathetically. In order to arrest potential cycles of decline, repointing should therefore only be performed after thorough assessment of current condition in every mortar joint and consideration of the short-term impact of the intervention, even if using more sensitive materials. This message was reinforced by findings that implied contextual factors, such as the aspect and topography of the masonry, outweigh the role of mortar type in local

Figure 3: The Equotip Piccolo surface rebound hammer was used to assess changes in Reigate Stone surface hardness, which can be related to changes in moisture content, across a two-year period at the Wardrobe Tower, Tower of London
Source: Author

moisture regulation. In order to maximise long-term benefits and prevent frequent intervention, repointing must therefore be part of a more holistic conservation strategy, which also protects repointed masonry from ongoing, rapid moisture ingress.

The findings of the field surveys also informed a computational model of the Wardrobe Tower, built using the hygrothermal simulation tool WUFI 2D, which investigated more closely the different pointing mortar scenarios identified in the field surveys. It found that joint width outweighed the role of mortar type in minimising moisture fluctuations at stone edges, providing further evidence that interventions need to be weighed up carefully in order to balance long-term benefits with the potential for widening joints as a consequence of depointing. There was also evidence that galletting joints could mitigate prolonged, deep wetting in wider joints. It was proposed that this technique should be investigated further in ongoing research, for example in a test wall.

RAPID NDT FOR ASSESSING THE SUCCESS OF DIFFERENT PAST CONSERVATION TREATMENTS

An NDT protocol designed to assess the long-term success of conservation treatments applied to Reigate Stone benefited greatly from an existing test wall, constructed in the moat of the Tower of London in 2001 to trial the use of hydroxylating conversion treatment (HCT). It was built to complement the trials of HCT on a small area of the Bell Tower. HCT was developed to enhance the adhesion of silanes to calcareous stones.[9] Laboratory testing had shown promising results on Reigate Stone. For the test wall, eight specimens of Reigate Stone from various sources had been cut in half and built into a rough, rubble-cast wall, with each half separated by a membrane. One half of each stone had been treated with HCT and the other half had been left untreated.

The study also provided an opportunity to evaluate two further past techniques.[10] A water repellent widely used at Hampton Court Palace (see Figure 4), believed to be a wax dating to the late 19th century. Limewash was used historically and reintroduced in the late 20th century as part of the lime revival and is a far more promising approach for ongoing conservation, at least for calcareous stone. Reigate masonry at the Tower of London was last limewashed in the early 1990s. Surface hardness (Equotip), water uptake (Karsten Tubes), and drilling-resistance (SINT Technology) (a minimally destructive technique which can measure changes in fabric strength along a depth profile) were measured at the test wall and a representative selection of other locations at the Tower of London and Hampton Court Palace. The study found that past treatments have been largely unsuccessful. The most promising techniques improve the underlying durability of calcareous stones, which are already less vulnerable to decay. It is not clear that any treatment is suitable for more vulnerable stones. While wax coatings can trap moisture, and there are concerns about water uptake during the application of HCT, limewashing was at worst benign and should be incorporated into future test walls to assess its suitability more fully.

Figure 4: A window at Hampton Court Palace that shows signs of treatment with a wax or oil, possibly dating to restoration work carried out in 1882.[11] The quoins, upper jambs and sill are Reigate Stone, the head and mullions are replacements
Source: Author

TARGETED NDT TO SUPPORT LONG-TERM MONITORING OF DECAY PATTERNS

One of several studies at the Bell Tower combined NDT surveys with long-term environmental monitoring, in order to link micro-climatic processes with observable patterns of decay.[12] Measurements using two different types of moisture meters (T610 and T660, Trotec) were combined with water uptake tests (Karsten Tubes) to determine a moisture profile, while visual assessment and dust trays were used to characterise the decay patterns. Distinct flaking and powdering decay patterns in Reigate Stone were associated with salt contamination and specific, moisture related, environmental mechanisms. Powdering was linked to deep wetting and a steady zone of near surface crystallisation. Flaking was linked to fluctuating humidity and a dynamic zone of sub-surface crystallisation. Each of these patterns dominates an area in the Bell Tower, with powdering found in the damp, cave-like lower chamber (see Figure 5) and flaking dominating the more exposed stairwell to the roof.

There were indications that material properties and historic contingency may contribute to these divergent decay pathways. The data collected during the surveys was used to design controlled laboratory experiments, the results of which suggested that the relationship between these variables, and crucially also the mixture of salts in the masonry, is more complex than the results of the NDT first suggested. The study serves to highlight both the value of NDT in building a causal hypothesis, and the caution that is necessary in over-interpreting their diagnostic ability.

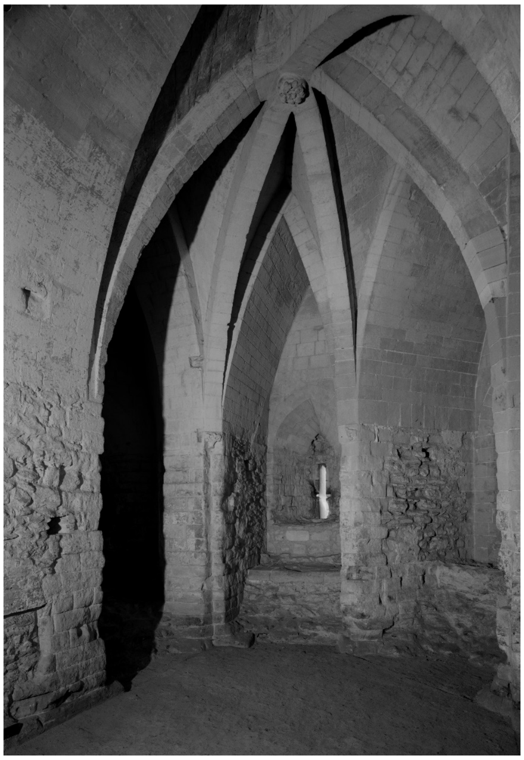

Figure 5: A photo dating to the 1960s of the asymmetric vaulted ceiling in the lower chamber of the Bell Tower, Tower of London. Historic photos and etchings revealed changes to the space that indicate its current microclimate may not reflect its long history
Source: HRP archives

GUIDANCE FOR USE OF NDT ON REIGATE STONE

Reigate Stone is highly variable and giving guidance on the expected readings using NDT devices is challenging. Some devices were not initially designed for use on soft, fragile masonry in-situ and can be very sensitive to small material or operator variations. Others can be highly susceptible to hidden factors, as conductivity/resistivity moisture meters are to salt content, which is common in Reigate Stone. Nevertheless, given the extensive testing done on Reigate Stone for this project, some anticipated readings for the T660 Trotec moisture meter and Equotip rebound hammer can be given.

On capacitance moisture meters, including the Trotec T660 device cited in this paper but also the more commonly available Protimeter device, measurements on Reigate Stone will frequently result in a maximum reading. Laboratory calibration indicates that a maximum reading does not necessarily mean the stone is fully saturated. When trying to ascertain moisture content on Reigate Stone, using several devices in combination is advantageous. The right combination will depend on what is being assessed. Combining the Trotec T660 (capacitance-based surface readings) with the T610 (microwave-based readings at depth) enabled a clearer understanding of the moisture profile. Combining capacitance meters with the rebound hammer enabled a better understanding of moisture content as it approached saturation, because it was possible to partially correlate changes in surface hardness with changes in high degrees of moisture beyond the limit of the moisture meter. Elsewhere, studies have shown that combining capacitance meters with conductivity/resistivity meters can provide some insight into levels of salt contamination.[13] When point readings using only one device or one type of device are possible, it can be helpful to group sets of readings. So, at the Wardrobe Tower, approximately 700 individual readings taken across four surveys using the T660 were grouped into three equal sets, representing wettest (readings of 199–200, which is the maximum reading), middle (185–198), and driest (below 185).[14] Although absolute values cannot be deduced, this approach enables a comparison of the wettest and driest parts of masonry in a specific area.

The Equotip rebound hammers were initially developed for testing the surface hardness of metal. Their use on masonry has been scientifically assessed in several studies and robust protocols have been developed for collecting reliable data. These depend upon taking a large number of readings. Up to 40 readings per stone is recommended on porous stone.[15] This can be challenging when taking measurements across large areas of Reigate Stone masonry, especially as measurements taken on Reigate Stone are prone to a disproportionally high number of error readings. Error readings are themselves interesting as they may indicate cavities or particularly fragile zones. In highly detailed surveys on single stones or small areas, the Equotip devices can be used to construct a precise map of surface and near surface structure, by combining single-impact and repeat-impact measurements and noting outliers and error-readings and establishing whether they are due to the operator or the material. This can be useful for assessing specific decay patterns. When investigating causal patterns or more broad distributions across large areas, it can suffice to group readings in key areas, such as adjacent to a particular type of mortar, or at a certain height. Fewer readings are needed on individual stones provided any grouped areas are broadly comparable. In large area surveys related to this project it was helpful to eliminate all readings below 200 HLD (Leeb Hardness), as most are likely to be inaccurate or require closer inspection. A reading of over 500 HLD is unusual on Reigate Stone; single-impact readings tend to measure between 280 and 400 HLD. Besides mineralogy, surface hardness is affected by factors such as surface treatment and moisture content. The use of rebound hammers should be combined with visual assessment and other NDT prior to any confident interpretation of their results. Both the Equotip Piccolo and the Equotip 550 were used with the D probe attachment in this project, with comparable results.

GENERAL FINDINGS, OPPORTUNITIES AND LIMITATIONS OF THE INTEGRATED METHODOLOGY

The overall implication of findings in each of these case studies is that past treatment and decay, present environment and underlying lithology each contribute to ongoing decay. When used in conjunction with findings made in laboratory and archival contexts, non-destructive field survey techniques, such as handheld moisture and surface hardness devices, can form a robust methodology for understanding the relevance of each of these axes of variability. The studies each focused on describing no more than two of these axes. The findings frequently served to highlight the relevance of the axis which had been omitted from a study; however, by linking together several studies at different scales and using the same or complementary techniques across those studies and in controlled environments, this research was able to describe a complex interconnected system and investigate it in meaningful detail. This scientific understanding can be used to identify controls within the system dynamics of masonry decay, which is the first step to developing sustainable conservation strategies. A tangible outcome of this research has been an improved set of parameters for incorporating into a new, long-term test wall experiment.

Figure 6 is a diagrammatic representation of the integrated methodology used in this research. It describes how NDT field surveys of the historic built environment can interconnect across several scales, and how this can in turn link to research in archival and controlled environments to construct a robust scientific framework. It also indicates the limits of this framework, with several external forces affecting the historic built environment which cannot be adequately described using scientific method. One of these is the notion of disturbance. This is an accepted concept in the study of earth systems, described as a force of external origin that cannot be predicted in the initial quantification of the overall system.[16] In the historic built environment, this could be climatic change or a large-scale climatic event which was not considered during the design of a historic building or subsequent remedial intervention. While such disturbances will continue to be common in attempts to describe with any precision the

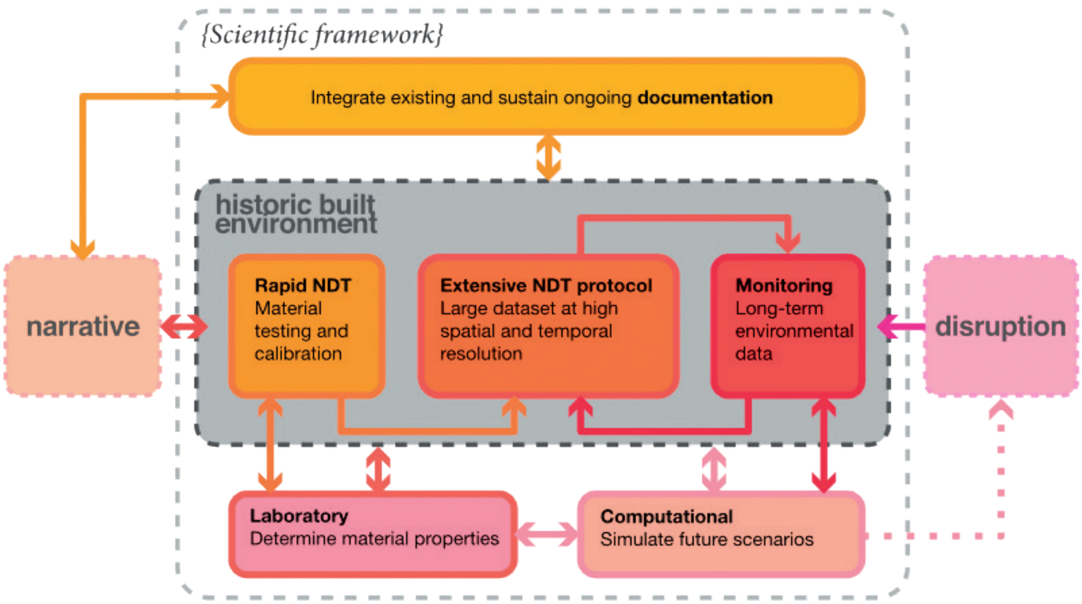

Figure 6: A diagrammatic representation of the integrated methodology used to investigate the framework of this research, and the external forces which are beyond its measurement
Source: Author

complexities of the historic built environment, advances in complexity science will increase the accuracy with which computer models are able to predict future events. More fundamental is the notion of narrative. Changes in cultural appreciation of the historic built environment play a major role in defining processes which control its physical change and vice-versa. Cultural heritage is by its very nature ephemeral; its quality is to provide narrative that transcends language and memory. By understanding its own limitations, however, science can take advantage of this idiosyncrasy by 'forming scaffolds from which new evidence becomes relevant […] narratives can track complex changes in a trajectory over time'.[17] In terms of informing scientific methodology, this demands rigorous documentation and trans-disciplinary collaboration. Historic building surveyors, operating as something of a 'first response unit' to the historic built environment, play a critical role in mitigating the uncertainty of these external forces.

Not every project will benefit from the time and resources that were available to this extended research. In particular, the valuable data gathered over the course of the two-year, in-depth NDT protocol at the Wardrobe Tower was logistically and operationally highly demanding. In many cases, historic building surveyors will feel pressure to diagnose pathologies on the basis of a single site visit and limited access. it is important, however, to understand not only the limitations of specific NDT, but also the broader approach to using them to collect data at different scales of investigation. Rapid protocols can only provide a snapshot. While they should not be used to justify significant interventions, they can provide a vital piece of evidence. Making appropriate use of this evidence may be a simple case of integrating an additional, complementary technique or setting up a short-term monitoring programme. In other cases, clear documentation will enable future surveys or other disciplines to gradually resolve limited findings into a bigger picture. At a policy level, further guidance on the limitations of commonly used NDT, appropriate conventions for dealing with misuse, and guidelines for designing case-specific yet methodologically comparable protocols are necessary.

CONCLUSION

Applying scientific method to the study of the historic built environment requires an integrated approach in order to make sense of complex system dynamics. Fieldwork can form the central piece in the jigsaw of a robust methodological framework, by fulfilling three criteria. It must:

(1) Be sensitive to cultural heritage, by relying mostly on non-destructive techniques (NDT) and integrating destructive testing only after rigorous investigation to identify locations of high scientific impact (ie representative, measurable) but low cultural value (ie tolerable intervention);
(2) Enable and inform the documentation needed for future generations to understand past analysis and intervention;
(3) Facilitate calibration with the laboratory experiments and computational simulations needed to build models of system behaviour. This can be achieved by integrating the NDT devices utilised in field surveys into the laboratory protocol. In long-term projects, test walls can enable a controlled measurement under real-world conditions.

In order to capture meaningful data, a successful fieldwork protocol can itself be broken down into a set of interlinked NDT methodologies. These can be designed to operate at different temporal and spatial scales. While long-term studies are important for monitoring response patterns under real world conditions, short-term studies can be of use when examining particular behaviours. Similarly, targeting and interlinking studies at different spatial scales can reveal both broad patterns and specific behaviours. When integrated with archival research and controlled testing, this approach will enable a range of analytical methods that can support more traditional surveying techniques.

The project summarised in this paper used this framework to investigating resilience in Reigate Stone masonry. This revealed an inherent complexity to understanding decay and deterioration, which prevents general practical guidance on conservation. Specific conservation strategies must be developed on a case-by-case basis. The more valuable yet less direct practical consequence of findings made in this project will be to support an approach which integrates targeted stone conservation with a holistic strategy to understanding and protecting the historic built environment. This demands rigorous and systematic documentation and interdisciplinary cooperation throughout a continuous process of management, maintenance, and care. Within this, historic building survey must exploit the opportunities of NDT in taking a robust, scientific approach to understanding the causes of decay.

AUTHOR'S NOTE

The author would like to thank Constantina Vlachou, Conservation Science Manager at Historic Royal Palaces, Heather Viles, Professor of Biogeomorphology and Heritage Conservation in the School of Geography and the Environment at Oxford University, and Ian Angus, Director of Carden & Godfrey Architects for their supervision of this research.

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