How monitoring can inform and support the retrofit of traditional buildings

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***Caroline Rye** has a background in both practical building and academic research. She completed one of the UK's first practice-based PhDs at Napier University in 2000 and went on to work as a research fellow at the University of Bristol developing practice-as-research methodologies. In 2010 she undertook an MSc in historic building conservation and then, in collaboration with Cameron Scott, was able to combine her two interests in buildings and research through the formation of ArchiMetrics Ltd. Caroline is the author of a number of research papers and reports including* The Responsible Retrofit for Traditional Buildings Report for the Sustainable Traditional Buildings Alliance (STBA) *and was part of the team that delivered the STBA Retrofit Guidance Wheel. She is a technical consultant on behalf of the STBA and sits on the Society for the Protection of Ancient Buildings' (SPAB) Technical Panel, for which, along with Cameron Scott, she has also undertaken research published as* The SPAB Building Performance Research Reports*. She has chaired the UK Centre for Moisture in Buildings Technical Working Group for monitoring and currently sits on the drafting panel for British Standards Committee CB/401-0-/01 – Building Performance Evaluation.*

***Cameron Scott** has been working in the field of sustainable architecture for the past 30 years, establishing the design studio Cameron Scott Limited in 2002. The building research element of Cameron's work has grown out of a desire to understand how completed projects function in reality so as to further inform the performance-based design process to optimise building quality and shorten the learning feedback loop. The aim is a functional architecture that provides a well-moderated internal environment for the minimum of inputs while keeping constructability and low building maintenance at the front of design considerations. Archimetrics Ltd has grown out of a mutual collaboration with Caroline Rye with a shared interest in sustainable architecture. Cameron is primarily responsible for developing the research questions, methodologies, protocols and analytics used by ArchiMetrics, along with designing and building the bespoke monitoring equipment required to answer the specific questions in hand. The principles of performance-based design, construction methodology and the importance of detail underpin Cameron's work in the fields of architecture, design and research.*

Abstract

The climate crisis creates an imperative to improve the energy efficiency of our traditional buildings and retrofitting offers opportunities to reduce their energy usage, while creating more comfortable spaces that are affordable to run. Little is known about the performance of traditional buildings, however, and retrofitting may also present risks, particularly with regard to moisture, for both fabric and occupants. Measuring and monitoring the performance of these building is a way to overcome *this knowledge gap. By deploying a variety of techniques, it is possible to engage with the complexity of a traditional building to ensure a more informed approach. Monitoring can be used to educate design decisions, provide more accurate input data for modelling, target measures, test treatments, measure effectiveness and guard against risks. It can improve the effectiveness of retrofitting and provide more confidence for retrofitting practices. This paper draws on our experience of providing monitoring services to illustrate some of the ways monitoring can be used to benefit retrofitting. Incorporating measurement and monitoring into retrofit projects ensures that both current and future retrofitting work will genuinely increase the energy efficiency of a traditional building while minimising risks.*

Keywords: monitoring, performance, retrofit, traditional buildings, moisture, U-values, air permeability

INTRODUCTION

Retrofitting can present many opportunities to improve the comfort, usability and energy performance of traditional buildings. It may also, however, pose risks for building fabric as well as building occupants and these risks may be particularly acute for older, solid wall (traditional) buildings. The performance of any building is dependent on upon multiple factors including its use, the location, orientation and exposure of the building, the materials involved in its construction, subsequent alterations and its state of repair. The heterogenous and historic nature of a traditional building further complicates this already complex picture. Older buildings built with solid walls, often using quite porous and permeable materials, may be subject to higher moisture loads than some more modern constructions. Some may be hard to heat but also rely on a certain degree of heat and air exchange to keep moisture levels in balance within fabric and living spaces.

Retrofitting is a relatively new field and there is limited information available to inform design decisions. The performance of traditional buildings is not well understood and is not a subject much studied or researched. Some of the tools conventionally used to make performance assessments may not be able to account for some aspects of an older building, the calculation of U-values for solid walls being one example. The materials and methods used in the construction of traditional buildings can be idiosyncratic and ambiguous, and the properties of many historic (and modern) UK materials remain undefined and do not feature in building performance modelling databases. There can, therefore, be a high degree of uncertainty when planning a retrofit for a traditional building.

Measuring and monitoring buildings, in situ, can provide knowledge and understanding of building performance to aid building design and other retrofit practices. Monitoring allows us to quantify aspects of a building's performance, such as its heat loss or air leakage, and in doing so move away from assumptions that may be made about older buildings and towards a more detailed and informed approach. By engaging with the physical building in the real-world measurements encourage retrofit thinking to move from the generic to deal with the more nuanced, specific circumstances of an individual building or set of buildings. Monitoring can be used at multiple stages throughout a project to give confidence to design decisions; it can be used to examine the condition of a traditional building and to better understand how it may be performing prior to retrofitting. Measurements can be used to calibrate building performance models with accurate, site specific, input data, and to test experimental treatments prior to wider deployment. Post-retrofit, monitoring can be used to measure success against design targets, keep a check on performance over the long term to see the effectiveness of improvement measures and/or to watch for adverse reactions. And the practices of monitoring and measuring itself require a physical interaction with the building which can often reveal information about aspects of its construction and function, details of wall construction for example, which can enhance approaches to retrofit.

PRE-RETROFIT

There are a variety of tests that can usefully be carried out pre-retrofit, two of the most straightforward being air permeability measurements and thermographic survey. These are 'spot tests' normally carried out over a day, although the timescale obviously depends on the size of the property. An external thermographic survey can be carried out during the winter months on a heated building, ideally a few hours before dawn. This is to ensure a reasonable internal/external temperature difference (≈10°C) and avoid the effects of residual solar heating on external surfaces. While not a quantitative exercise, an external thermographic survey should show discontinuities across the external surface of the building envelop, some of which may be the inevitable result of building geometry. Such a survey will, however, show where the greatest heat loss is occurring and hence, in addressing this, where the highest gains may be made (see Figure 1). Some locations will be obvious — doors and glazing, for example; however, the survey might reveal hidden or less obvious aspects of the building, such as earlier timber frame structures, redundant through-wall vents and pipework, voids or cavities. Likewise, under similar conditions, an internal survey can be carried out to the same effect. Thermal bridges may be identified or, if the building is already insulated, areas of missing or poorly fitting insulation may be found. Therefore, rather than relying on assumptions about the likely sources of heat loss through the building envelop, a thermographic survey can identify and confirm both expected and unexpected sites, thus allowing the subsequent retrofit to be designed and specified to work comprehensively throughout the building.

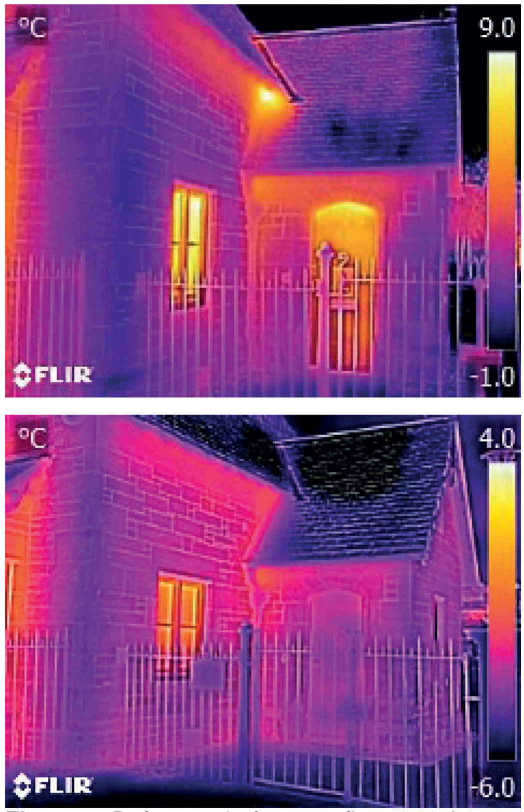

Figure 1: Before and after retrofit external thermography — East Elevation, Holyrood Park Lodge

An air pressure test conducted using a blower door fan can establish an air permeability figure ($m^3/hr/m^2$ – AP50) for the building, as well as providing other more detailed information about air leakage that may be particularly useful when retrofitting traditional buildings. Knowing an air permeability value prior to undertaking retrofit work gives an indication of the degree of air tightness work that maybe required to 'improve' a property and avoids excessive reductions in air exchange. If retrofit designers are using models to make assessments of likely performance, having an exact

AP50 figure as a base case input value means that 'before' and 'after' retrofit energy performance predictions, be they for cost savings, air quality or CO_2 reductions, will be more accurate. It is often assumed that older buildings are draughty; however, this is not always borne out by measurements, partly because some traditional construction methods, such as an internal wet plaster finish directly on to a solid masonry wall, can seal the surface and limit infiltration.[1] In an older building, air leakage is more likely to be the result of particular parts of a construction, in which case a more 'diagnostic' air pressure test is essential. It is possible to carry out more targeted air pressure testing which, by isolating various aspects; windows, lofts, chimneys, etc. quantifies the contribution these individual elements might be making to the overall leakage of a building (see Figure 2). This allows a retrofit team to identify where they should concentrate their efforts and employ the most suitable techniques to reduce excess leakage. More detailed air pressure testing can be complimented by the use of a thermographic camera, where, once again with a ≈10°C internal/external temperature difference, an internal survey can be carried out under depressurised conditions. Colder, external air is drawn into the structure at points of weakness in the envelope and this infiltration is revealed as low temperature streaking within a thermographic image (see Figure 3). While this test does not reflect the performance of the building under normal conditions, it exaggerates infiltration pathways, some in unexpected places, which, once again, allows these areas to be targeted for air tightness work.

Once air tightness interventions are designed and implemented, air pressure testing and thermographic surveys can be carried out at various stages during the construction phase to check the installation of these measures. Furthermore, if air pressure testing is repeated post-retrofit (and this may be required for compliance reasons) this will allow the success of the work to be quantified, as well as acting as a check against any

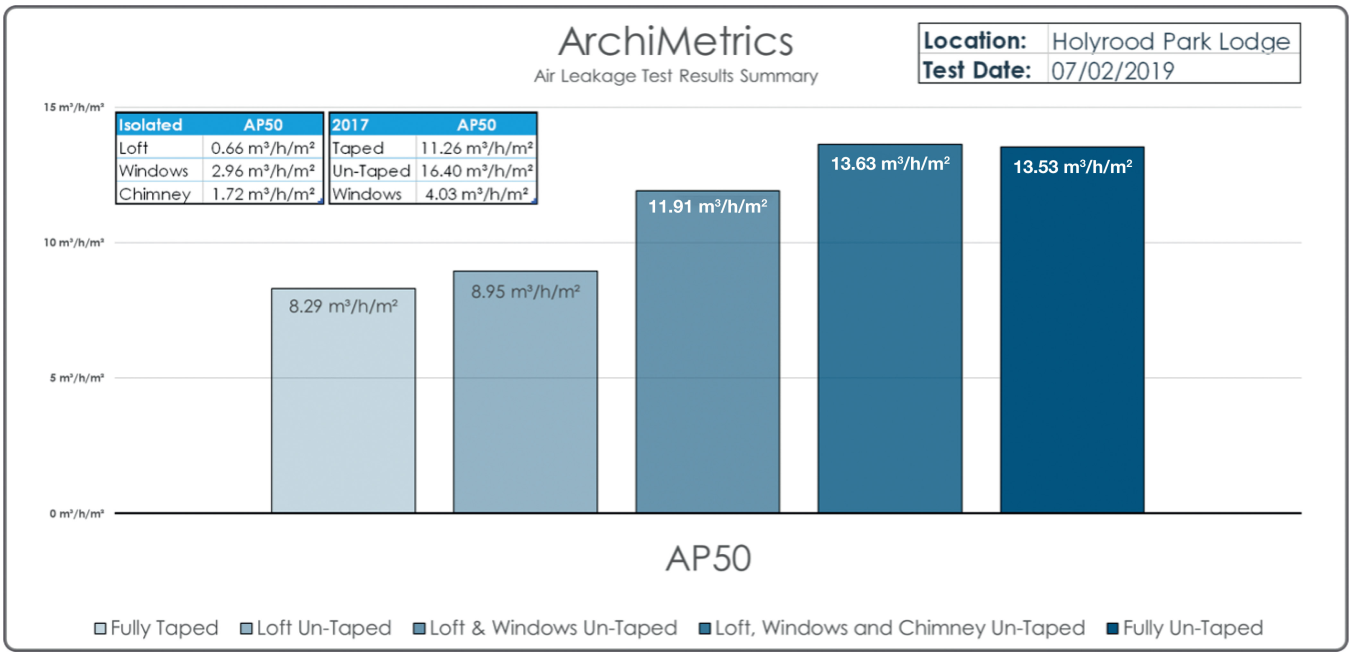

Figure 2: Air permeability of isolated building elements — loft, windows and chimney, Holyrood Park Lodge, Edinburgh

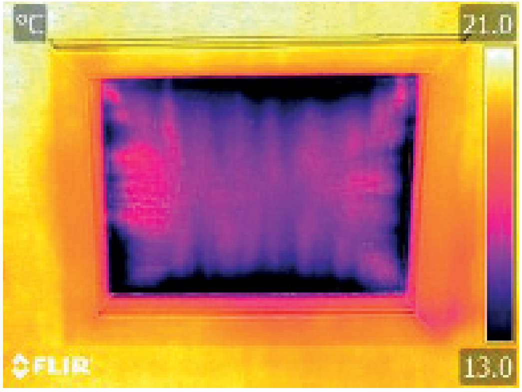

Figure 3: Air ingress around a loft hatch under depressurised conditions

design performance targets that may have been set for the project, in turn, providing useful feedback for designers and contractors.

There are other measurements that take place over a longer time scale which can be carried out pre-retrofit and, although they can be used for buildings of all types, maybe of more relevance for traditional buildings. In particular, the calculation of U-values for solid wall buildings can be problematic, especially if these walls are built of a variety of materials with unknown thermal conductivities and underdefined construction details. In these cases, it is possible to make a measurement, or measurements, as an in situ U-value for the walls in question. Following BS ISO 9869, these measurements use a heat flux plate fixed to the internal surface of the wall and the simultaneous measurement of internal and external temperatures. An internal/external temperature difference averaging 10°C is also required for the two-to-three-week measurement period, meaning these tests can only effectively be carried out in a heated building over the colder winter months. As with air pressure testing, gaining a more informed understanding of the heat loss from these walls ultimately allows for more effective retrofit interventions and also reduces associated risks. An accurate pre-retrofit U-value can be used in design models to determine the energy saving benefits that might be derived from wall insulation. Knowing the thermal transmissivity of the wall also means that the correct amount of insulation can be specified to achieve a defined post-retrofit target — potentially saving money, avoiding material waste and excessive cooling of the element. This last point is of particular concern for solid walls which may be constructed from quite porous materials; low fired bricks or local stone and may therefore, at certain times of the year and depending on local climate and exposure, carry a higher moisture load. Such structures may rely on evaporation occurring from both sides of the wall at certain times of the year, and/or a degree of heat transfer through the element to maintain a manageable moisture load over an annual cycle. The risk of high moisture is most prevalent with regard to timbers embedded within these walls, such as joist ends, although other, sometimes overlooked timbers such as bearers and lintels, are also commonly found in the walls of traditional buildings. Because of this, the insulation of solid walls made of porous materials where moisture may reside quite deep inside a wall structure, particularly if the wall is subject to wind driven rain, needs to be well informed.

The behaviour of moisture within building elements is difficult to measure; however, because of concerns around the risks of moisture accumulation in retrofit projects we developed a method by which the moisture profiles of elements, principally walls, may monitored. This technique, which is destructive and requires small cores to be drilled into building substrate, may be particularly relevant for listed buildings whose fabric is protected and for buildings that contain materials or artefacts that are sensitive to moisture. We started by making measurements of temperature and relative humidity (RH) at a number of different points through a wall section, more recently, for certain projects, we are making measurements of material moisture content

(%MC). This ensures that we are looking at moisture behaviour in two states, as a vapour and a liquid and each set of measurements has its own advantages and disadvantages. RH is fast to react, less effected by salts and good for capturing the detail of moisture responses particularly in drier walls. We are also able to use RH measurements to see whether and where the wall may be experiencing dewpoint conditions (100 %RH) and for how long. These measurements also enable us to look at vapour profiles as absolute humidity (AH) a measurement of the weight of vapour in the air, g/m^3, without the influence of temperature. %MC is ideal for substrates where saturation conditions might arise or for materials with specific %MC risk thresholds. Measurements are taken every five minutes ensuring fine grain detail and the moisture monitoring often takes place over quite long periods of time in order to build up a picture of how the wall is responding through different seasons, enabling us to identify the underlying trends or drivers of moisture behaviour. Determining whether the moisture measured within the wall represents a risk is not necessarily straightforward. Other than timber there are no clear risk thresholds for other common building materials and whether a material can be judged to be 'wet' or not is dependent upon the specific qualities of the material in question. Risk thresholds for RH measurements are better known and are often quoted as 75 per cent or 80 %RH, although these tend to be based on observations regarding mould growth on internal surfaces not interstitial decay and in both cases would require high RH to be maintained for an extended period of time.[2] It is quite normal for us to observe high, +80 %RH within a wall over winter and then see the wall 'recover' over the spring and summer months.

These moisture measurements, sometimes made in tandem, can be installed in a wall prior to retrofitting, particularly if internal wall insulation (IWI) may be a consideration. In this way the base case moisture performance of the wall can be analysed to identify whether there are any underlying anomalies and where and how 'drying' takes place within the substrate over an annual cycle, which may in turn inform approaches to insulation treatments. In cases where hygrothermal modelling is part of design processes (something that is required by BS ISO 5250: 2021 for solid walls subject to internal insulation as part of a retrofit) interstitial hygrothermal gradient monitoring can be used as part of an accuracy check for these models. This is something that may be deemed vital for work on statutorily protected and other buildings given that, as BS 5250 acknowledges, the material properties databases which accompany these models may not be accurate or even available for UK construction materials leading to a degree of uncertainty in their model predictions. For New Court at Trinity College, Cambridge we worked with Max Fordham engineers and provided details of 'real world' temperature and RH responses measured through the section of a 'typical' unimproved wall. Engineer James Freeman used this data to 'calibrate' a model of this same wall that he had built using WUFI hygrothermal simulation software, making adjustments to the model inputs to create a better 'fit' between the responses of the simulation and reality (see Figure 4). This calibrated model was then used as the basis for predictions of the long-term performance of the wall once internal wall insulation had been added. In this way, as with a pre-retrofit air permeability value and measured in situ U-values, moisture monitoring can provide inputs for, and hence greater confidence in, the predictions made by building simulation models, be they concerned with energy usage, heating and cooling loads, sizing plant, heat and moisture transfer, etc.

In many ways the monitoring at New Court, which is ongoing, might act as an

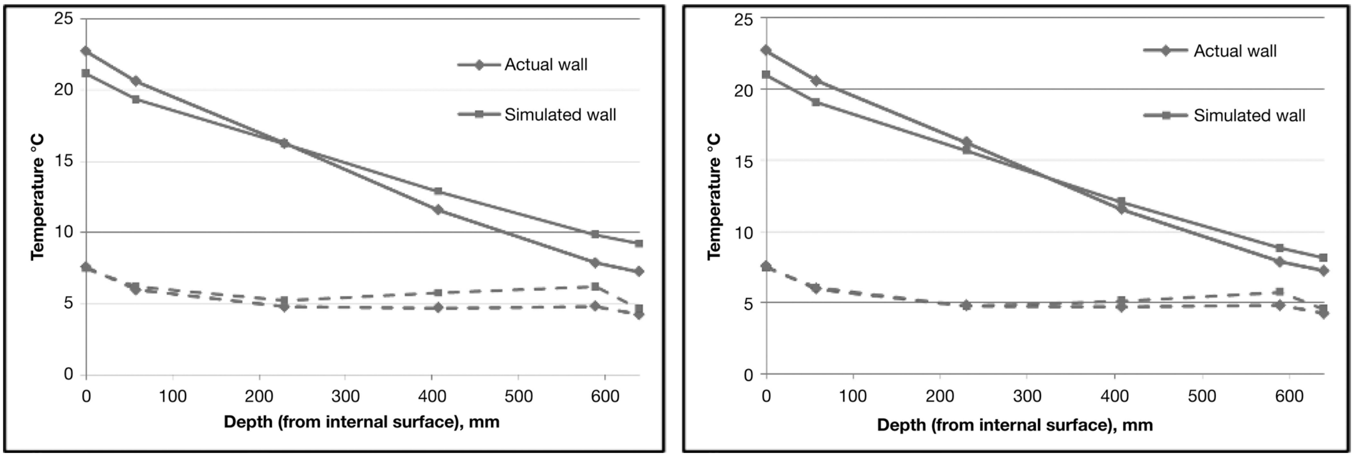

Figure 4: Calibration of WUFI model output using monitored site data for New Court 'wall', Trinity College, Cambridge
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exemplar as to how a retrofit project can make use of and gain from building performance monitoring.[3] Thermographic survey, air pressure testing, measured in situ U-values and interstitial moisture monitoring, as well as straightforward room condition (temperature and RH) measurements, were all undertaken pre-retrofit and used to inform design decisions.[4] In discussion with English Heritage (as was) and Cambridge City Council, however, further checks were required before permission for the retrofit of the Grade I listed building could be granted permission. An experimental 'test' room was created, where the proposed internal wall insulation was installed on one of the walls judged from modelling to be more 'vulnerable', alongside a 'control' wall. Monitoring included the measurement of U-values and moisture profiles through the two walls, as well as looking at potential cold bridges at ceiling and wall junctions and conditions within historic timbers, cornice and picture rails, encased behind the insulation. This pre-construction monitoring mostly served to provide reassurance regarding the retrofit design, the application of 72mm of woodfibre IWI resulted in a significant reduction in the in situ wall U-value, 0.58 W/m^{2}K down to 0.28 W/m^{2}K, with no increase in the overall moisture profile of the wall or increased incidence of dewpoint or interstitial condensation.

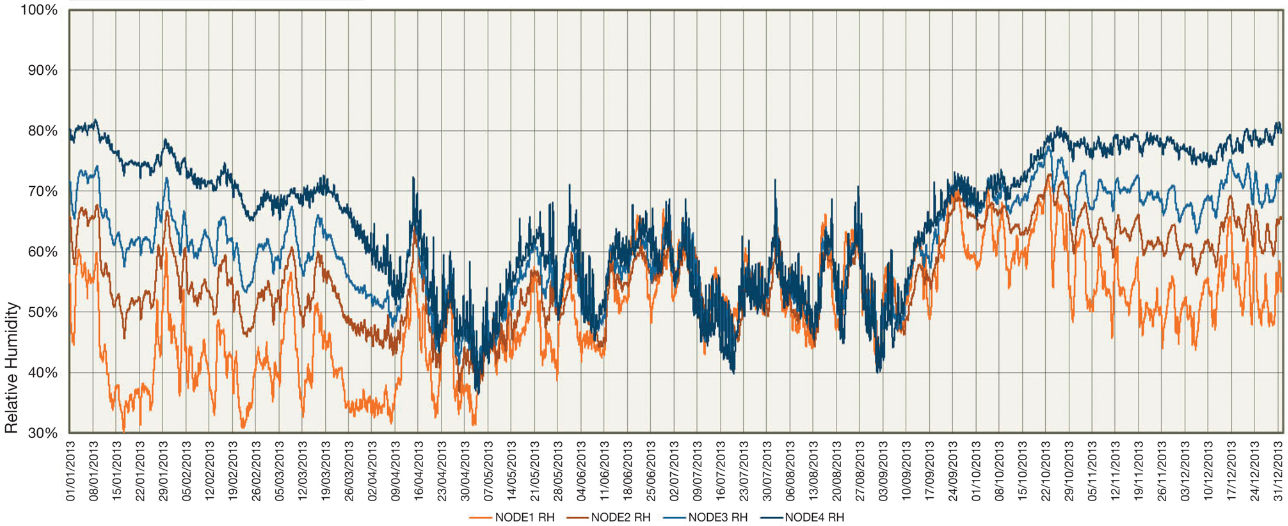
The prototype monitoring also revealed some unexpected findings regarding the lime parge coat applied to the internal surface of the masonry wall, used to level it, and eliminate air pockets. This wet material is usually left until it is dry to the touch prior to the installation of the insulation board, as was the case here. Monitoring, however, revealed a protracted drying time for this material, where the parge coat reached equilibrium over a period of six months (see Figure 5). This discovery changed site practices where it became a requirement that the parge coat be left for an extended period of time prior to the application of the woodfibre to minimise the risk of trapping excess moisture. An incidental observation also concerned a difference in the quality of RH responses through the test wall in comparison with those of the uninsulated masonry — where a more volatile 'signal' was measured particularly from sensors in closer proximity to the internal side of the wall, n1 and n2. We attributed this to the reduction in air movement through this part of the structure as a result of the presence of the parge coat which sealed the wall and along with the

Project:	Trinity
Building:	New Court
Location:	16 Control
Start:	01/01/2013
End:	31/12/2013
Logger:	AMIG/03
Material:	Brick with L&P lining
Thickness:	625mm

ArchiMetrics

Relative Humidity Over Time

RH %	Minimum	Maximum	Average
Internal	23.45	72.58	44.73
NODE 1	29.55	72.46	50.03
NODE 2	36.88	72.83	56.00
NODE 3	38.96	77.48	60.52
NODE 4	36.48	81.82	65.00
External	16.14	94.37	71.71
Average	**30.24**	**78.59**	**58.00**



Project:	Trinity
Building:	New Court
Location:	16 Test
Start:	06/02/2013
End:	31/12/2013
Logger:	AMIG/09
Material:	Brick with PavaDry IWI
Thickness:	665mm

ArchiMetrics

Relative Humidity Over Time

RH %	Minimum	Maximum	Average
Internal	35.84	72.93	52.95
NODE 1	41.68	60.81	50.62
NODE 2	53.14	84.95	63.79
NODE 3	45.83	73.15	60.72
NODE 4	42.38	83.03	67.42
External	0.10	90.72	68/09
Average	**36.50**	**77.60**	**60.60**

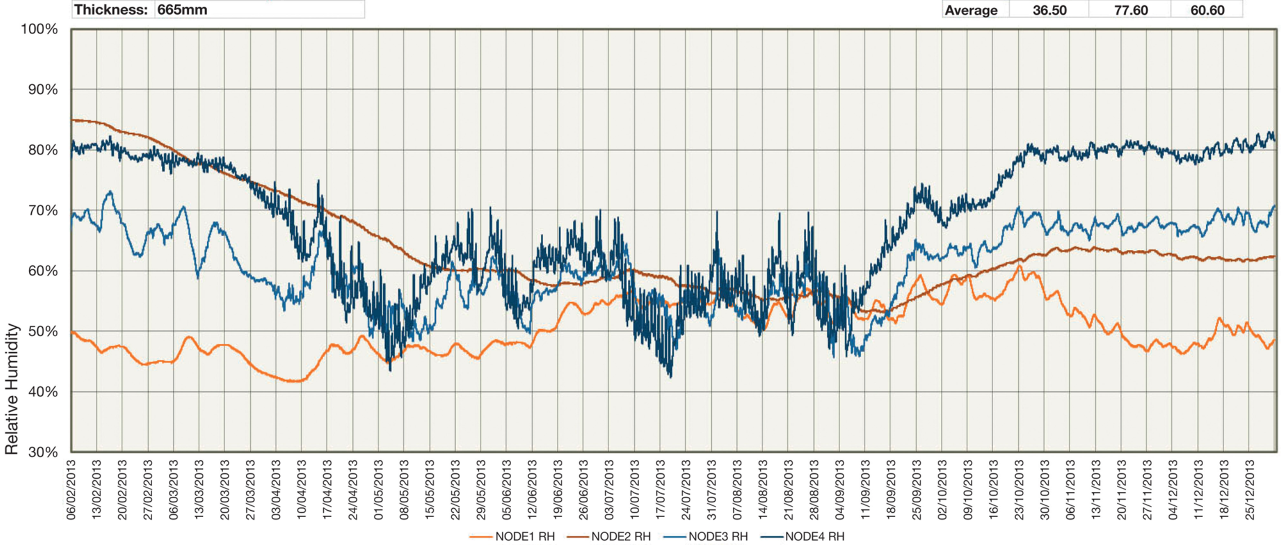


Figure 5: Control and test wall RH over time — experimental IWI install, New Court, Trinity College. (Node 2 trace showing 'drying' of the parge coat)

insulation acted as an air barrier. In contrast, the original wall was finished with a lath and plaster lining set off from the internal wall face by battens which created a void behind the lining. Something that was eliminated by the installation of internal wall insulation leading to additional energy efficiency gains for the project.

POST-RETROFIT

Thus far this paper has described situations where monitoring is used to provide information to aid design and specification work pre-retrofit. Monitoring can also be used post-retrofit to ensure that work has met design intentions and/or is not causing harm to building fabric or occupants. Vitally, post-retrofit monitoring can also provide measured evidence from the building in use to determine the success of certain retrofit interventions to deliver genuine energy efficiency, or otherwise, and improve retrofit practices. At New Court, a long-term fabric and room condition monitoring scheme was made a condition of planning consent, alongside a 'mitigation strategy' which identified what steps would be taken in the event of adverse conditions being reported. This scheme measures moisture within 30 of the insulated walls across four floors and on all elevations at New Court, as well as in selected floor, wall and roof timbers. Temperature, RH and carbon dioxide, CO_2, is measured within the rooms and five 'wet rooms', kitchens and bathrooms, are also subject to room condition and interstitial fabric moisture measurement. In situ U-values have also been measured for the retrofitted walls. Findings of the monitoring are reported at half-yearly intervals including a detailed report provided on an annual basis. The monitoring shows satisfactory performance with, on average, a 51 per cent reduction in heat loss through wall elements, no long-term accumulation of moisture within building materials and no persistently high RH/MC within walls, vulnerable timbers or within the rooms themselves, including wet rooms where moisture loads might be higher. A mechanical ventilation and heat recovery system was installed as part of the retrofit and internal environment measurements show this delivers good air quality to the rooms.

As part of this 'watching brief' an online system of email alarms was instituted triggered by measurements of high, +80 %RH. The alarm system is designed primarily to indicate when fabric is at risk from high moisture levels as a result of interstitial condensation and/or long-term moisture accumulation leading to conditions conducive to the growth of rot and mould. It is normal for us to see high RH during the winter towards the external face of some of the more exposed walls at New Court, but RH above 80 per cent does not normally persist over the long term. On one occasion, however, alarms were triggered during the summer, signalling the presence of high moisture throughout the whole section of one of the monitored walls. Although not visible internally, readings of very high RH inside the wall were caused by water flooding down through the wall from an overflowing blocked parapet gutter on the roof above. Because this flooding took place over the summer when the rooms are unoccupied, by alerting the college to a problem which might have gone unnoticed for some time, the alarm had the additional benefit of helping to limit the damage caused by this flood water. Subsequent to this event, the RH and %MC monitoring installed in this wall has then allowed observations to be made of the fabric drying over a number of consecutive years, and the risk presented by high moisture and the possibility of mould growth receding (see Figure 6). This type of post-retrofit monitoring, as well as allowing a check to be made on normal 'in-service' conditions within a building, can additionally provide reassurance where, in the event

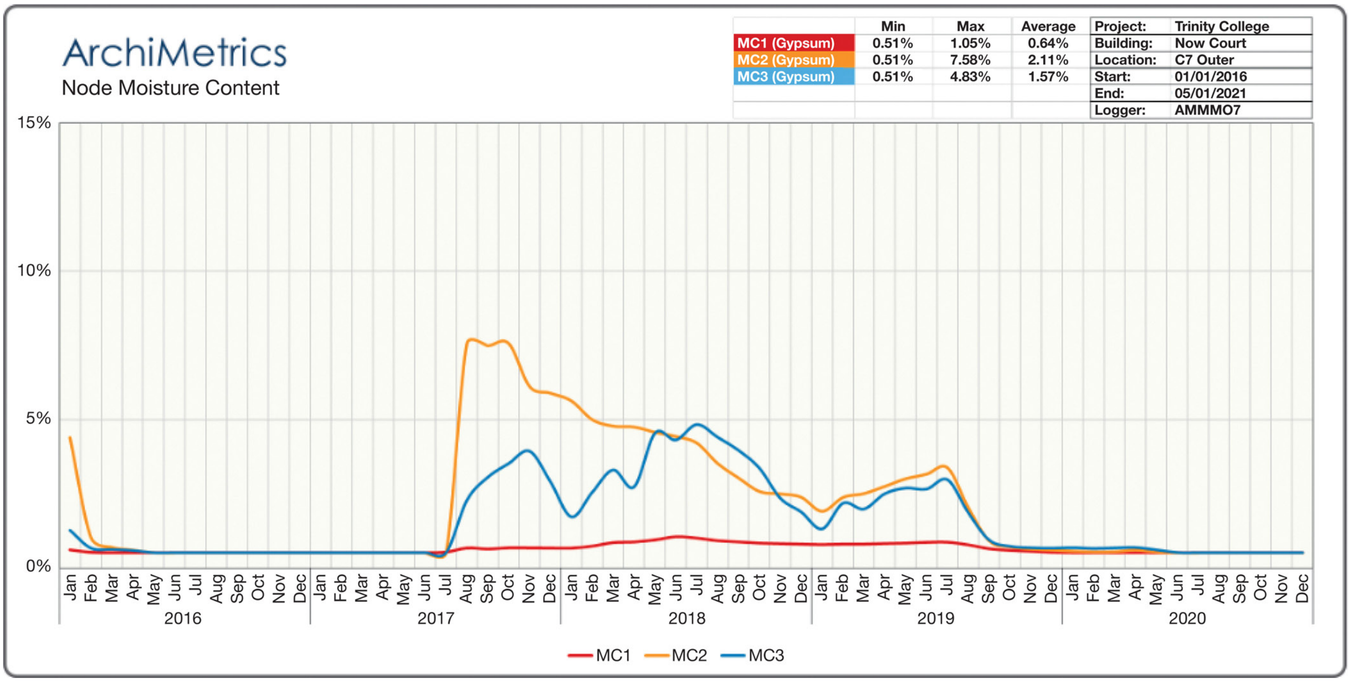


Figure 6: Material moisture monitoring, showing flooding and recovery %MC response, New Court, Trinity College

of the escape of water or another a-typical scenario, monitoring can demonstrate that retrofit is robust and can recover. In this instance an additional site visit was made where the condition of the woodfibre insulation, among other materials, was inspected and gravimetric measurements of %MC carried out. This showed that the insulation material itself had not been damaged by the flooding and was thus able to continue to fulfil its insulative purpose. Used in this way, the long-term monitoring followed up by site inspection provides reassurance and proof of concept in that, because of the moisture-open nature of both the historic and new insulation materials, moisture has not become trapped and has been able to evaporate until the fabric is seen to return to its 'normal' moisture equilibrium with no damage or long-term detrimental effects on performance.

Older buildings may not be well understood or well described by the conventional tools of design and building physics used by the building industry, so measuring performance is a crucial way that we can improve our understanding of how these buildings work. The project at New Court is just one, albeit very thorough, example of how monitoring can be used through the stages of a retrofit project to give confidence to work undertaken in the name of energy efficiency. And since measurements need not be limited to the types of examples cited above, there is potentially no limit to the questions that can be answered, or decisions that can be better informed, if consideration is given to monitoring early on in a project.

Looking at and recording the performance of buildings in the real world is one way to manage the complexity of retrofitting a traditional building. Monitoring and measuring performance can take account of the diverse idiosyncrasies of materials, construction types, alterations, building condition, climate and exposure, as well as being a means to gain an insight and feedback on the success of chosen retrofit strategies to further inform future projects.

Monitoring can provide greater certainty for retrofit practices and in doing so can ensure that our older historic buildings can continue to be used and stand as symbols not only of the ingenuity of the past but also of the present.

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