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Retrofitting Historic Timber-Framed Buildings in the UK: Monitoring the Risk of Increased Moisture Content.

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Abstract

The risk of unintended consequences arising from the energy retrofit of buildings, especially concerning moisture movement through the building fabric, is well-recognised. As highlighted by Publicly Available Standards (PAS) 2030 and 2035 this is particularly relevant to buildings of traditional construction, defined as those "consisting of solid brick or stone external walls, or pre-1919 timber-framed external walls with any infill". This article focuses on this last construction typology, presenting ongoing research, funded by Historic England, monitoring the hygrothermal performance of four pairs of mock-up replacement infill panels for timber-frame walls. The chosen materials, informed by current guidance, are wattle-and-daub, expanded cork, wood fibre/wood wool, and hempcrete. Each pair of panels features two finishes: one with a Natural Hydraulic Lime (NHL) 3.5-based render, and the other with a non-hydraulic lime/hemp mix. The panels are installed as the northern façade of a test cell, exposed to Cardiff's climate, with controlled internal conditions during the heating season. Since December 2019, moisture content (%) has been monitored by measuring electrical resistance every 30 minutes in a total of 60 positions. Previously published results from the initial 18 months of monitoring reported no evidence of interstitial condensation, with wetting and drying cycles directly corresponding only to wind-driven rain events. However, following four years of monitoring, there now appears to be evidence to suggest that interstitial condensation is occurring within both the traditional wattle-and daub and the composite wood fibre/wood wool infill panels. Although predicted by simulation and previous trials, this condensation might have previously been obscured by wind-driven rain. Its emergence in both traditional and retrofitted infill materials underscores the complex nature of moisture behaviour in this construction typology. This development is under ongoing review, and the monitoring of case study buildings is planned. The results will eventually inform best practice guidance for the energy retrofit of historic timber-framed buildings in the UK.

Introduction

As the pressure increases to improve the energy performance of all existing buildings, including our historic building stock, it is important that we fully understand the risk of unintended consequences of retrofit actions[1]. These can include negatively impacting indoor air quality and the movement of moisture through the built fabric, particularly in older (pre-1919) buildings of traditional construction, as indicated by Publicly Available Standards (PAS) 2030[2] and 2035[3]. In the UK, buildings of traditional construction are predominately those with solid masonry external walls[4], and as such form the focus of research assessing the risk of energy retrofits[5-7]. However approximately 68,000 historic timber-framed buildings survive in the UK[8]. For these buildings, changes to hygrothermal behaviour and resultant moisture accumulation resulting from the replacement of damaged or inappropriate infill materials with those with improved thermal performance has the potential to increase the risk of fungal decay and insect infestation[9]. This article discusses research, funded by Historic England, aimed at evaluating the risk of degradation in these historic timber structures.

Figure 1. 17th century timber-framed buildings with 19th century alterations, Newtown, Powys, Wales (Source: author, 2024).

Historic Timber-Framed Buildings in the UK

For the purposes of this article, historic timber-framed buildings are those where the external walls consist of a framework of loadbearing timbers, with non-structural infill, built before1850. Fully timber-framed buildings are believed to have been developed around the late 12th century[10], however the majority of those that survive today date from the 16th and 17th centuries[8]. Following the great fires of the late 17th century, principally in London but also in other cities such as Northampton and Warwick, the construction typology fell out of favour as regulations were implemented to restrict its usage[11]. The second half of the nineteenth century saw a revival in the appreciation of the timber-framed aesthetic with the development of the Victorian Olde English Style[12]. However, by this time, decorative timbers were merely applied to solid masonry construction, as opposed to being true timber-frames. This practice was repeated in many inter-war suburbs[13] and can still be seen today in the design of speculative housing developments, underlining the cultural significance of true historic timber-framed buildings, and the importance of their conservation.

Opportunities for retrofit

Given the heritage value of our historic timber-framed building stock, any work to these buildings must be undertaken with great care and understanding. Historic England stresses that “it is important to remember that infill panels within the timber-frame can have as much historical significance as the frame itself”[9], and as such, where original or historic infills do survive, especially wattle-and-daub, their retention should be prioritised. There are however often opportunities to improve energy efficiency and hygrothermal comfort. Despite being the focus of this article, the thermal upgrade of the walls should not be the first retrofit action, and should only be considered following maintenance and repair, and must form part of a whole house approach[14]. When improving their thermal performance is appropriate, from a purely technical perspective, the introduction of external wall insulation EWI presents the best thermal performance and has the least risk of increasing moisture retention[9]. However, given the significance of exposed timber-frames, this is often only possible where previous cladding, either weatherboarding or continuous plaster is already present. Where the timber-frame is already exposed on both sides and no historic infill survives, or repair to the timber-frame requires its removal, the options that form the focus of the research presented in this article become a potential solution.

Risks

As previously discussed, the introduction of thermal insulation to any building envelope will affect the movement of moisture through the built fabric and may result in moisture accumulation[3]. For historic timber-frame buildings this poses the risk of increasing moisture content within the timber-frame and creating ideal conditions for biological degradation, through insect larvae and fungal decay[15] (Table 1). Factors influencing this risk include external and internal climatic conditions, detailing, workmanship and material choice, with the use of impervious infill materials and finishes to be avoided[16]. Even with moisture permeable materials, there is still the potential for both surface and interstitial condensation, and the trapping of moisture at the exposed joint between infill and frame.

Table 1. Optimum hygrothermal conditions for common UK biological timber threats [17]

	Beetle and their Larvae				Fungi		
Common Name	Powder-post	House Longhorn	Woodworm	Deathwatch	Dry Rot	Oak Rot	Cellar
Latin Name	*Lyctus linearis Goeze & Lyctus brunneus*	*Hylotrupes bajulus*	*Anobium punctatum*	*Xestobium rufovillosum*	*Serpula lacrymans*	*Donkioporia expansa*	*Coniophora puteana*
Moisture Content (%)	8-25	15-25	>12	>15	>26	>28	>25
Temperature (°C)	26	20-30	22	>10	17-23	5-40	20-32

Assessing the Risk - Previous research

A literature review conducted between 2014 and 2017 identified guidance on the retrofit of historic timber-framed buildings[9, 18-23] but failed to encounter scientific research assessing the associated risk of moisture increase. To address this knowledge gap, the author has undertaken research into this area since 2014, with funding initially from the Association for Preservation Technology International Martin Weaver Scholarship, followed since 2019 by grants from Historic England's Heritage Protection Commissions Open Programme. Initial digital hygrothermal simulation using WUFI® pro 5.3 on a range of infill solutions indicated that material properties, orientation, and prevailing climatic conditions each influenced moisture content. Nevertheless, there was no extended identified exposure to hygrothermal conditions conducive to biological attack[24]. Given the limitations of digital simulation, which include the lack of detailed material data for historic materials, and the use of idealised homogeneous constructions, field measurements were undertaken in a 16th century domestic property in

Suffolk. This confirmed that the use of impervious infill materials and finishes can lead to serious problems of moisture retention and subsequent biological decay[25]. However, the opportunity to monitor a project applying best practice guidance was not forthcoming. Tests were therefore conducted on three panels mounted between two climate-controlled chambers. The panels were all finished on both sides in a render based on NHL 3.5, and had the following infill materials: wattle-and-daub; a wood fibre/wood wool detail suggested by Historic England[20]; and expanded cork board, as suggested by Ty Mawr Lime Ltd. These were subjected for three weeks to forced conditions which were expected to create interstitial condensation, followed by a further two weeks of diurnal cyclical conditions that aimed to replicate typical internal and external climatic conditions. The results of that experiment did measure interstitial condensation in the wattle-and-daub and wood fibre/wood wool infills under the forced conditions but this did not reoccur during the diurnal cyclical testing[26]. Given that the phenomena in question occur over an extended time scale, and the need to assess the risk of interventions into buildings that have already survived hundreds of years, longer-term monitoring was desirable. This gave rise to the research covered in this article.

Methodology

To enable long-term monitoring, a test cell was constructed at Cardiff University (Figure 2), measuring 3.5m x 1.9m x 2.2m (width x depth x height). The test panels form the external envelope of the northern façade, their outer face exposed to the Cardiff climate. The internal environment is controlled during the UK heating season (Oct/Nov-March/April), with a temperature set point of >21°C and relative humidity of >60%. Outside of this period, internal climatic conditions are left free-running to replicate typical domestic building conditions in the UK. A pedestal mounted rotating fan, mounted behind the heater and humidifier circulates the air to avoid stratification. The fan is in operation throughout the year.

The dimensions of these panels were determined based on a study of 100 representative historic timber-framed buildings, which revealed that 53% were square-framed and 47% were close-studded. Square panels averaged 785mm x 950mm, while close-studded panels averaged 305mm x 1830mm. Given the test cell's configuration, close-studded panels were chosen to allow for the monitoring of eight adjacent panels at the same height above ground level.

Figure 2. Test cell showing north façade prior to application of external render. Panels left to right, wattle-and-daub, expanded cork board, wood fibre/wood wool composite and hempcrete. Source: (Author's own, 2019)

The array of eight panels was constructed using reclaimed oak and facilitates the monitoring of four different infill solutions: wattle & daub, expanded cork board, composite wood fibre/wood wool[20], and hempcrete[22] (Figure 3). Professional firms, known for their expertise in working on historic buildings, were engaged to ensure realistic implementation. Each pair of panels was finished internally and externally with either a finish based on natural hydraulic lime NHL 3.5 (Secil™), chosen as the most typically specified conservation finish, or a non-hydraulic lime hemp plaster supplied (Ty Mawr Lime Ltd.).

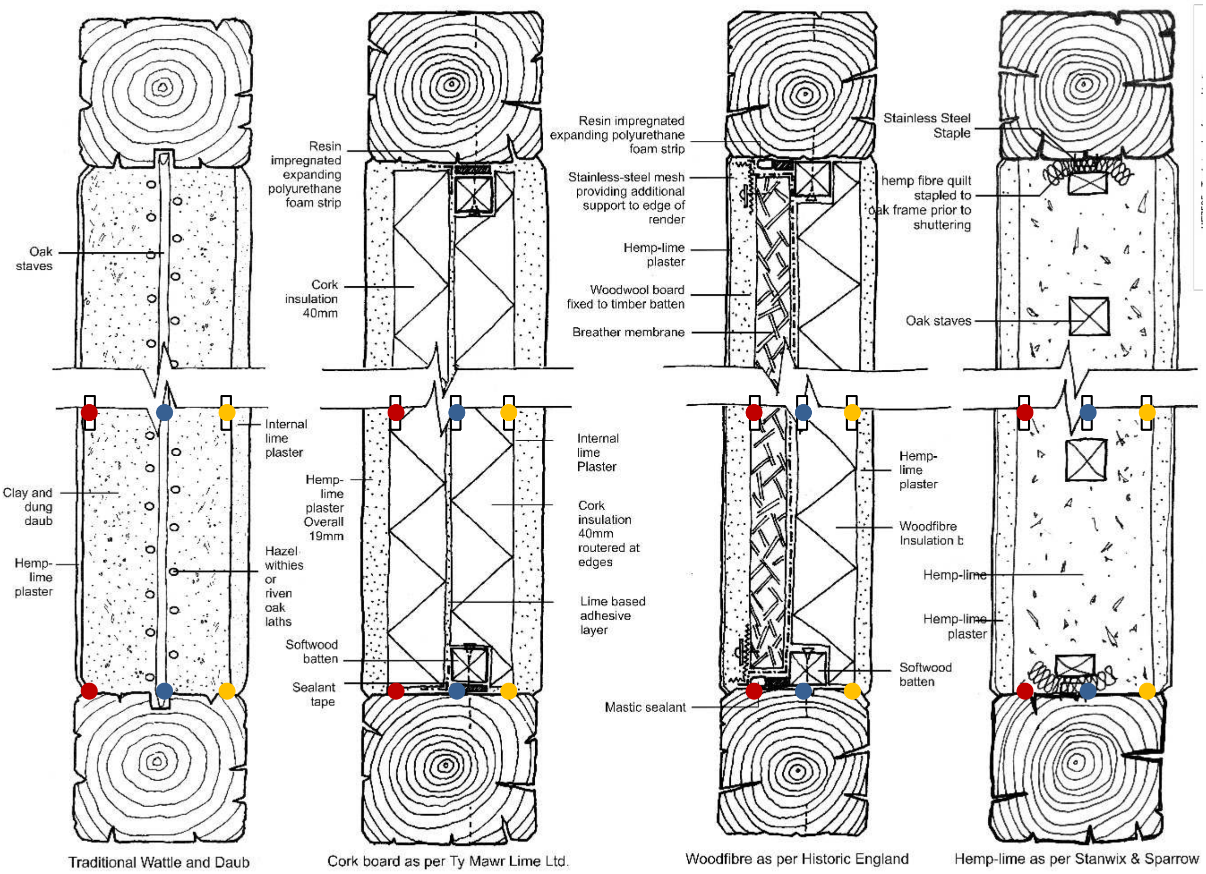

Figure 3. Sections showing panel infill details and monitoring locations. Red- external I, Blue- central I, and yellow- Internal (i). Source: (Author's own based on [20, 22]*)*

Interstitial hygrothermal sensors were embedded at 60 positions. These covered the centre of the panel, the centre point of the horizontal junction with the wall plate at the base of the infill, and at mid-height of the vertical junction between infill and timber stud. At each location, sensors are positioned at the interface between the external render and infill material, at mid-depth, and at the interface between infill and internal plaster. The sensors consist of Type T thermocouples to measure temperature (°C) and pairs of stainless-steel screws embedded the oak frame to determine moisture content (%) by electrical resistance measurements. In the centre of the panels, where no framing is present, short lengths of split oak lath were introduced so that all the moisture content measurements are made in the same material. Recordings are taken via a Campbell Scientific™ CR1000 at 30-minute intervals. All wiring is arranged to minimise the creation of additional direct heat and moisture paths. A calibration exercise based on that undertaken by Dr Brian Ridout for pine[27] was conducted to establish the conversion factors from electrical resistance (Ω) to moisture content (%) for oak. This gave the following equations (1&2) for the calculation of the moisture content:

If R<0.31225 Then $$MC = (0.1912\ R)^{-0.192} \tag{1}$$

If R>=0.31225 Then $$MC = (0.2263\ R)^{-0.0271} \tag{2}$$

Where:

R = Resistance

MC = Moisture content %

The measurements must also be corrected for the effect of temperature using equation 3 [27]:

$$MC_K = \frac{(MC + 0.567 - 0.0260x + 0.000051x^2)}{0.881(1.0056)^x} \tag{3}$$

Where:

MC=moisture content as measured %
MC_k=temperature corrected moisture content %
x= surface temperature +2.8°C

Additional measurements included internal and external temperature (°C), relative humidity (%), precipitation (mm), air pressure (mbar), wind speed(m/s), wind direction, and direct solar radiation incident on the test panels (W/m^2). Thermal performance assessments were conducted using thermography and in situ U-value measurements during heating seasons. These have been previously reported[29] and are not the subject of this article.

Results

Initial tests results have already been published following the first six months of monitoring (post-initial drying period)[29] and after eighteen months[30]. These both indicate that those panels finished in the render based on non-hydraulic lime maintain a lower moisture content than those with the NHL 3.5 based render, and present faster drying times following wind-driven rain wetting events. Problems were identified at the perimeter details of the wood fibre/wood wool, and expanded cork board infill panels, potentially due to the use of an impermeable sealant at this point. However, neither identified the occurrence of interstitial condensation, with the wetting and drying cycles of all panels directly correlating with measured wind-driven rain events. There follow the latest results covering four complete years of monitoring from 12/12/2019 to 18/01/2024.

As can be seen in Figure 4, as previously reported[30], the majority of the increases in moisture content can be seen to correspond to measured instances of wind-driven rain, many of which are named storm events. With the predicted increase in the frequency of these winter storm events[31], there is an inherent increase in the risk of higher moisture content of timber-frame infill panels regardless of retrofit.

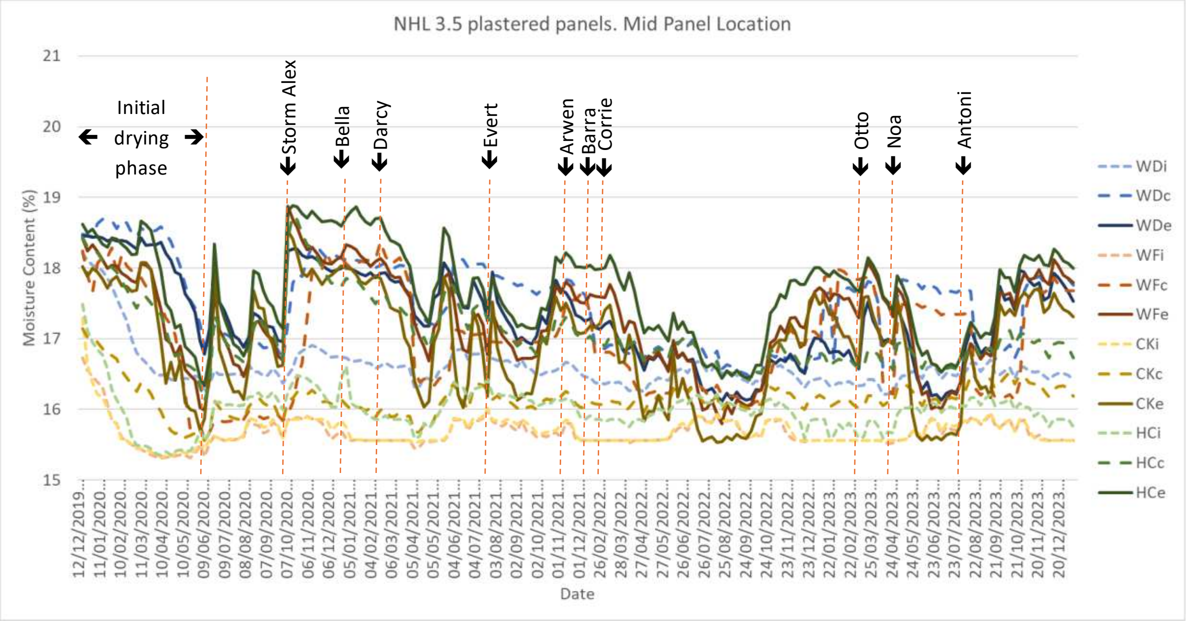

Figure 4. Moisture Content Measurements at mid-panel location of panels with NHL 3.5 based finishes 12/12/2019 – 18/01/2024. With UK named storm events overlaid. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC-Hempcrete. i-internal, c-centre, e-external.)

However, as highlighted in Figure 5, in mid-January 2023 and again at the end of October 2023 there is also a measured increase in moisture content in the centre of the wattle and daub (WDc), and the wood fibre/ wood wool panels (WFc). This occurs in both those panels with finishes based on NHL 3.5 (Figure 4) and lime-hemp (Figure 5). Noticeably, these increases had a considerable offset from the increase at the outer layer resulting from wind-driven rain. Whilst this could represent the time taken for moisture to penetrate the panel, they could also suggest the occurrence of interstitial condensation.

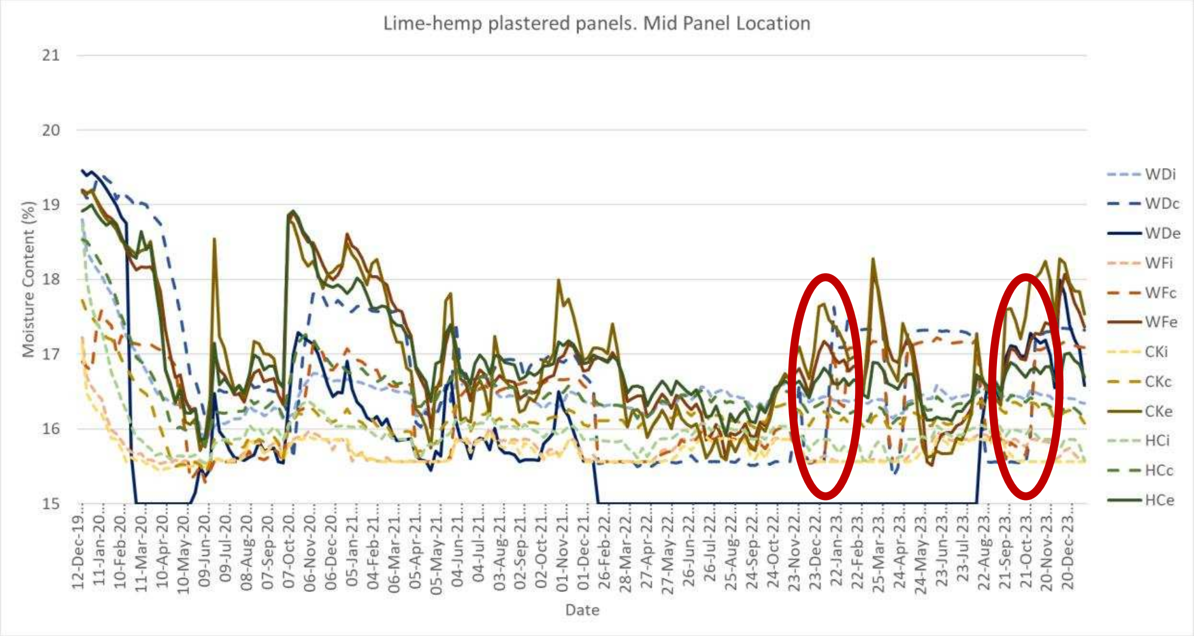

Figure 5. Moisture Content Measurements at mid-panel location of panels with Lime hemp-based finishes 12/12/2019 – 18/01/2024. With potential evidence of interstitial condensation highlighted. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC-Hempcrete. i-internal, c-centre, e-external.) Note: Due to connection issues, no data was collected for monitoring point WDe from March-May 2020 and Jan 2022-August 2023.

Using the average internal and external temperature and relative humidity during this period in Glaser calculations (BS EN ISO 13788:2012), it can be seen that there is a risk of interstitial condensation (Figure 6 & Figure 7). This also raises the possibility that previous instances of interstitial condensation may have been masked by increased moisture content arising from wind-driven rain. The northern orientation of the test panels was chosen to reduce the influence of wind-driven rain, which is predominantly from the south-west in Cardiff, however, during storm events this is increasingly frequently from the north or multidirectional.

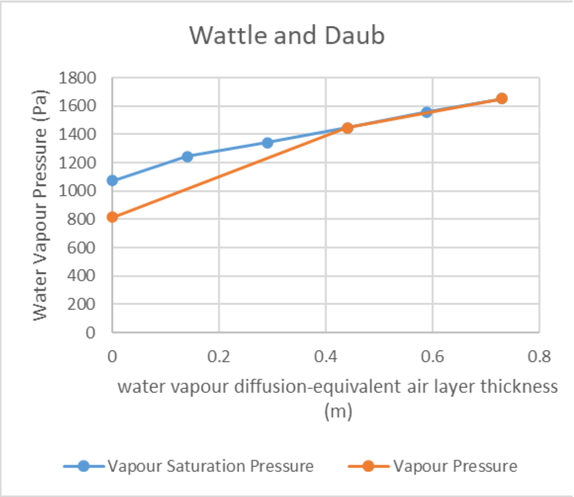

Figure 6. Glaser calculation for Wattle and Daub with NHL 3.5 based finishes. Exterior to left and interior to right.

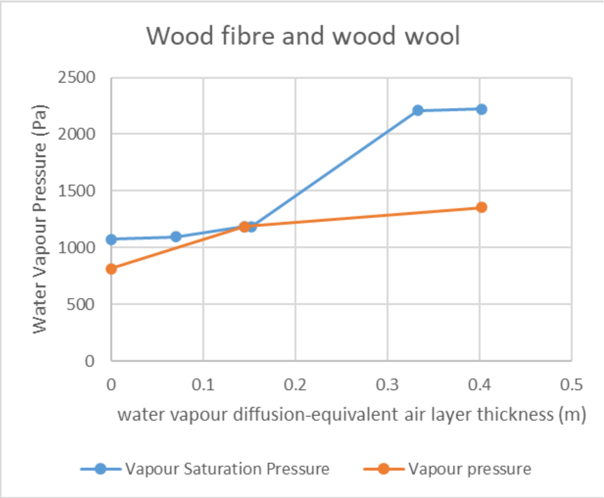

Figure 7. Glaser calculation for wood fibre and wood wool with NHL 3.5 based finishes. Exterior to left and interior to right.

A similar situation can also be observed at the monitoring positions at the junctions between the panels and the oak frame of both the wood fibre and the wattle and daub panels (Figure 8 & Figure 9). This potentially calls into question the previous conclusion that the impermeable sealants, included in the junction detail for the wood fibre/ wood wool panels, were trapping moisture at this point that was entering via capillary action. There is no such sealant in the perimeter detail of the wattle-and-daub panels, which shows a similar behaviour to the wood fibre, whereas the cork infilled panels, which do have a perimeter seal, do not show any comparable marked increase in moisture content.

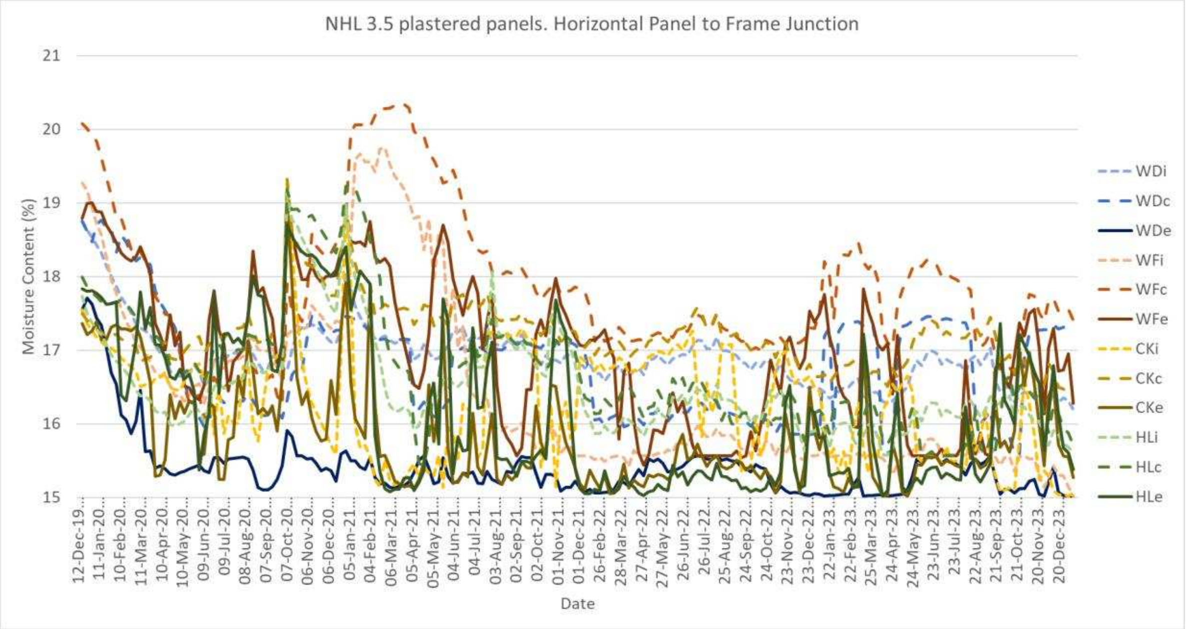

Figure 8. Moisture Content Measurements at horizontal panel-frame junction for panels with NHL 3.5 based finishes 12/12/2019 – 18/07/2023. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC-Hempcrete. i-internal, c-centre, e-external.)

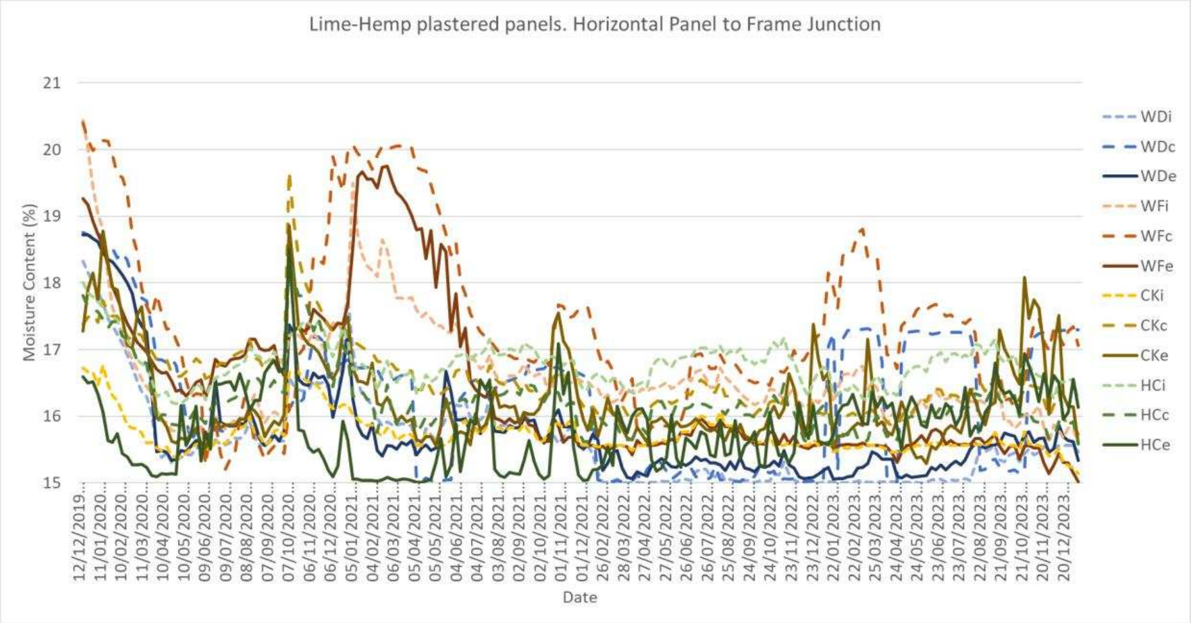

Figure 9. Moisture Content Measurements at horizontal panel-frame junction for panels with Lime-hemp based finishes 12/12/2019 – 18/07/2023. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC-Hempcrete. i-internal, c-centre, e-external.)

Discussion

The possible occurrence of interstitial condensation within the wood fibre/wood wool retrofit solution does suggest an increased risk in moisture accumulation. In discussion with material suppliers, it has been suggested that this risk could be reduced by omitting the wood wool render carrier board and only using the wood fibre board, which itself can receive render directly. This would avoid the use of two materials with different densities and water vapour resistance factors (μ). Amending the Glaser calculation to a single layer of wood fibre board, equal in thickness to the wood fibre/wood wool sandwich, shows that the risk is removed. There has however been concern raised when speaking to practitioners over the robustness of this detail and achieving a secure perimeter junction in practice. Given that the suggested occurrence of interstitial condensation has also been observed in the traditional wattle-and-daub infill, this calls into question the severity of this risk. It is possible that such increases in moisture have occurred previously in these traditional buildings. As long as moisture permeability is maintained, and this can dry out, this may not need to be a significant concern.

Ongoing work

Data collection and analysis is ongoing and is currently funded until January 2025. In addition, over the past year, as part of the Historic England funded project, the School of Engineering at Cardiff University have been undertaking detailed material characterisation of all the test panels' constituent materials. This process will soon be completed, and the data used to undertake further digital interstitial hygrothermal simulation. It is hoped that by doing so, a better match between simulated and measured data may be achieved, allowing simulations to be conducted for other UK climates and future climate predictions.

Talks have also begun with professionals involved in potential case studies where some of the retrofit details covered in this research have or will be put into practice. The author would be interested in hearing from any other practitioners working in this field.

Conclusions

Further work is still required to fully assess the risks associated with the energy retrofit of our historic timber-framed buildings. The research covered in this article emphasises the value of long-term monitoring. The results underline the complexities involved, and that work must be considered holistically and on a case-by-case basis, assessing the particular condition and significance of each building, and the elements that form it. It is however clear that the moisture permeability of any infill material and detail is paramount, with the non-hydraulic lime-based renders maintaining a lower overall moisture content and quicker drying times. Whilst previous research by the authors had suggested that interstitial condensation was not occurring, evidence now suggests that this may have been masked by wetting resulting from wind-driven rain. This however would appear to be occurring in both the wood fibre/wood wool retrofit solution and the traditional wattle-and-daub, and as such could be something that historic timber-frame buildings have coped with in the past. The upcoming further work with digital simulation, and the anticipated in situ case study measurements will provide further knowledge to inform the complex decisions faced by conservators, and practitioners, enabling better risk management, especially with regards to reducing moisture build up and retention. At the same time it will enable researchers and policymakers to continue to develop nuanced guidelines and best practices for the sustainable conservation of our historic timber-framed buildings.

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