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Evaluating the hygrothermal performance and associated benefits and risks of replacement infill panels for historic timber-framed buildings in the UK.

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Abstract

Historic timber-framed buildings, although a small part of the UK's historic building stock, contribute to UK national cultural identity. However, their thermal performance is typically inferior to their masonry counterparts, and their defining exposed frames limit retrofit options. Where historic infill is missing or damaged, there exists the opportunity to infill with thermal insulation. However, this may increase moisture accumulation leading to biological decay. The research in this paper, funded by Historic England, has monitored the hygrothermal performance of eight experimental infill panels in Cardiff, since 2019. Four infills materials were monitored, wattle-and-daub, a wood fibre/wood wool composite, expanded cork board, and hempcrete, within a reclaimed oak frame. Two finishes were applied, NHL 3.5 and sand render, and a non-hydraulic lime with hemp shiv aggregate. Moisture content and temperature were monitored at nine positions within each panel. Over five years, significant moisture fluctuations were recorded. Initially no interstitial condensation was identified, with wetting and drying cycles corresponding with wind-driven rain events. However, in the last few years, incidences of interstitial condensation were identified in the wood fibre/wood wool composite and the wattle and daub. Additionally, extended periods of high moisture content were recorded at some perimeter junctions. Overall, those panels finished in the less moisture permeable NHL 3.5 show higher moisture contents and longer drying times. Comparative WUFI® Pro simulations are now underway using measured climate data and material properties. The final results will inform best practice guidance as we aim towards a sustainable future for these iconic buildings.

Highlights

- The paper focuses on an under-researched typology, UK historic timber-framed buildings.
- Results highlight the complexities of retrofitting historic buildings, especially those of timer-frame construction.
- The use of moisture permeable materials is key, as is the detailing and workmanship of the junction between frame and infill.
- Beware of unneccessary changes of material densities and water vapour resistance factors (μ) within infill build-up.
- The increase in wind-driven rain events increases the risk to this building typology in the UK.

Introduction

External walls of often exposed timber structural frames, with non-loadbearing infill, were once one of Britain's most common construction techniques (Innocent, 1971, Braun, 1940), with examples still surviving from the 13th century (Harris, 2010). Despite today only representing 7.5% of the pre-1850 housing stock in England (Nicol et al., 2014), 1.6% in Wales and almost non-existent in Scotland (Naismith, 1985) and Northern Ireland (Gailey, 1984), the surviving 68,000 buildings (Whitman, 2017) constitute an important component of the UK national identity (Ballantyne & Law, 2011).

Figure 1. C15 timber-framed building, "Cordwinders", High St, Lavenham, Suffolk (Author, 2017)

Due to their materiality, construction and wall thickness, the thermal performance of these buildings is typically worse than that of their masonry counterparts (Demaus, 2017), and well below that of modern regulations. As such, there is pressure to undertake energy retrofits with the aims of improving occupant hygrothermal comfort, lowering energy bills and reducing carbon emissions in line with UK (BEIS, 2019) and EU goals (OJEU, 2018). It is however important to safeguard their cultural heritage (OJEU, 2018, Historic England, 2017). As such, in some instances where the timber-frame is exposed both internally and externally, the only option for thermally upgrading the walls is through the replacement of the panel infill with one with a lower thermal conductivity. However, this is limited to those cases where historic infill is already missing or damaged, and brings with it the risk of moisture accumulation, which in turn could lead to biological decay.

The aim of the research funded by Historic England and presented in this paper, is to assess the hygrothermal performance of eight different experimental infill panels, within a reclaimed oak exposed timber-frame, over a five-year period. It is hoped by doing so to inform guidance and best practice, reducing risk, whilst enabling these buildings to continue to provide adequate accommodation for years to come.

Methods

Following *in situ* measurements at a number of historic timber-framed buildings across the UK (Whitman & Prizeman, 2016, Whitman and others, 2018, Whitman, 2020), experimental mock-up panels were chosen for the methodology as they permit both increased monitoring opportunities and greater control over variables. Initial laboratory testing conducted on three infill materials between two climate controlled test chambers at the University of Bath's Building Research Park near Swindon, funded by the Association of Preservation Technology International's Martin Weaver Scholarship, produced interesting results and confirmed the advantages of physical monitoring over digital simulation (Whitman and others, 2020). However, the high running costs of running two climate chambers limited the duration of the tests to five weeks. For the methodological design of the research presented in this paper, it was therefore decided to install the experimental mock-up panels as part of the north facing façade of the external envelope of a test cell, the internal hygrothermal climate of which would be controlled only during the UK heating season (Oct/Nov-March/April). During this period a 1kW heater has a set point of 21°C and a humidifier keeps relative humidity >60%. During the non-heating season, the internal conditions are free-running, replicating the conditions in most UK domestic properties. The northern orientation was chosen to minimise the impact of climatic variables, such as direct solar radiation and wind-driven rain.

The aforementioned initial laboratory testing, through the review of a representative sample of 100 exposed timber-framed buildings, had established an almost equal split between square-framed panels (53%) and close-studding (tall thin panels 47%) (ibid.). Therefore, in order to maximise the number of panels with comparable monitoring locations, close-studding was chosen, using the calculated average size of 305mm x 1830mm. This enabled the monitoring of four pairs of panels infilled with i) wattle-and-daub to replicate the most traditional construction; ii) a wood fibre/ wood wool composite detail as published by Historic England (McCaig & Ridout, 2012); iii) expanded cork board and iv) hempcrete, two infill solutions commonly being used in practice. One panel from each pair was finished internally and externally in a Natural Hydraulic Lime NHL 3.5 based render, a typical specification by conservation architects, and the other in a lime-hemp render as suggested by Ty Mawr Lime Ltd. All panels were framed in reclaimed oak.

Within each panel, interstitial temperature (°C) was measured using embedded Type T thermocouples and wood moisture content (%) using electrical resistance. Monitoring positions are located, in elevation, in the centre of each panel, at the midpoint of the horizontal junction between the panel and sill beam (lower member) and at the midpoint of the vertical junction between the panel and stud (upright member). At each of these there are sensors at three depths, i) the interface between external render and infill material; ii) midpoint of infill material; and iii) at the interface between internal render and infill material (Figure 2).

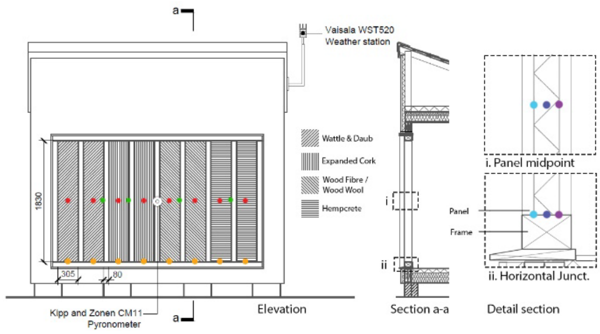

Figure 2. Monitoring positions in elevation (Red-centre of panel, Orange- midpoint of horizontal junction, Green- midpoint of vertical junction) and section (Cyan- interface external render and infill, Blue- midpoint of infill, Purple- interface internal render and infill).

All sensors were wired back to a Campbell Scientific® CR1000™ datalogger, extended with an AM16/32B™ multiplexer, with readings every 30 minutes. External climate (temperature (°C), relative humidity (%), precipitation (mm), wind speed (m/s) and direction, and direct solar radiation on vertical face of panels (W/m^2)) and internal climate (temperature (°C) and relative humidity (%)) were also recorded.

During the heating seasons 2019/20 to 2024/25 *in situ* u-value measurements were undertaken annually according to BS ISO 9869-1:2014 (British Standards Institution, 2014) using type T thermocouples and Hukseflux® HFP01 heat flux plates connected to a Campbell Scientific® CR1000™ datalogger. External thermography was also completed in February and November 2020 using a FLIR® B250™ and February 2025 using a FLIR One® Edge™.

Following the first two years of monitoring (Dec 2019-Dec 2021), dynamic digital numerical simulation of interstitial hygrothermal conditions was undertaken with the software WUFI® Pro 5.3 using the measured internal and external climatic condition, and proxy materials taken from the software's existing database. This predicted similar but not identical hygrothermal conditions. As such, since then, detailed material characterisation has been undertaken, the methodology for which is beyond the scope of this paper. A second round of simulations using this measured physical properties and the updated software WUFI® Pro 6.6 is currently underway.

Results

Interstitial Moisture

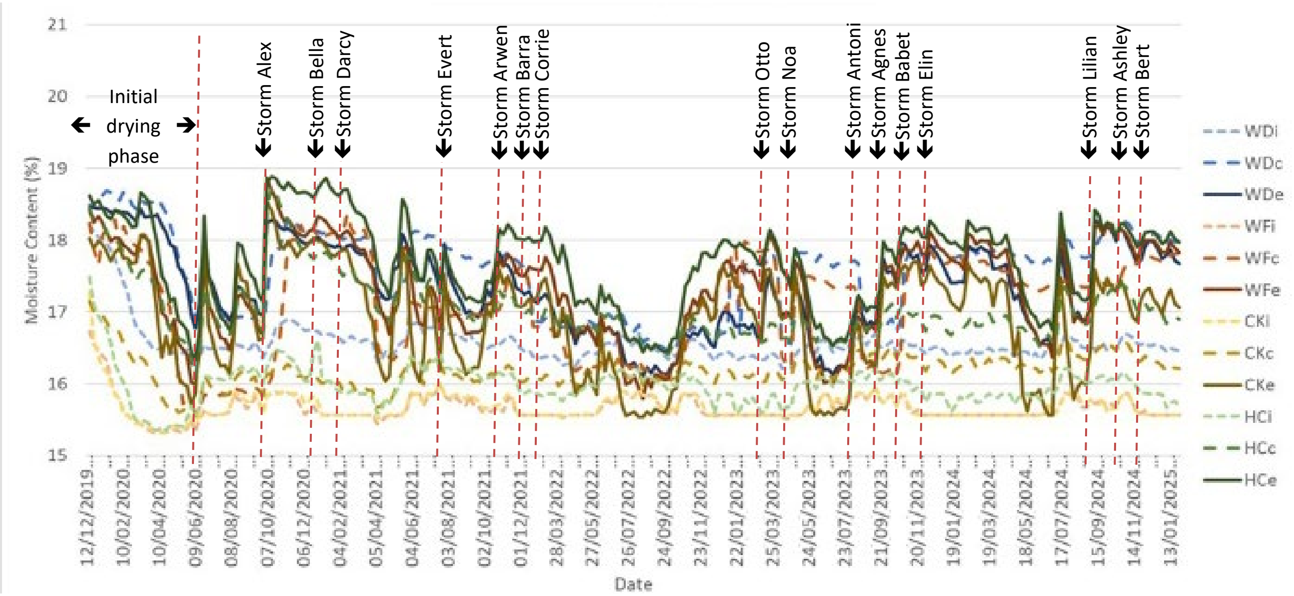

Figure 3. Wood Moisture Content at mid-point of NHL 3.5 finished panels 12/12/2019 – 05/02/2025. With UK named storm events overlaid. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC-Hempcrete. i-internal, c-centre, e-external.)

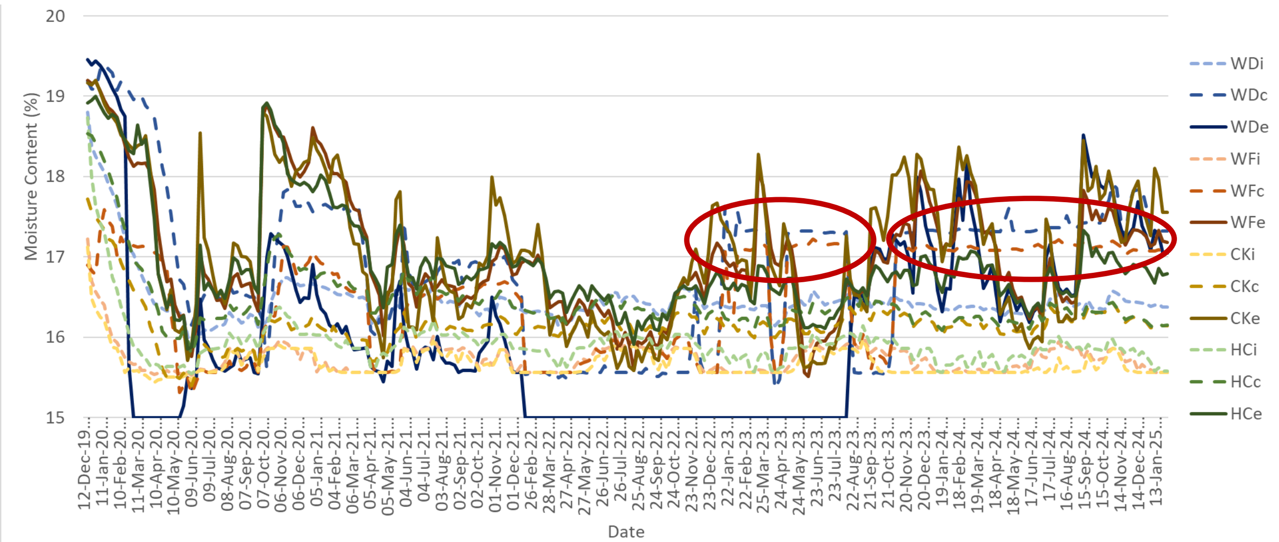

Figure 4. Wood Moisture Content at mid-point of Lime-Hemp finished panels 12/12/2019 – 05/02/2025. High moisture content at centre of Wattle & Daub (WDc) and Wood Fibre (WFc) panels highlighted.

The results for the moisture content monitoring (Figure 3 and Figure 4) show a pattern of wetting and drying for all panels. These cycles generally coincide with wind-driven rain events, frequently related to named storms (Figure 3) during which winds can come from the north. For the first three years of study, no evidence of measured interstitial condensation was apparent. However, since the beginning of 2023, high levels of moisture has been recorded at the central monitoring position in those panels with wattle & daub, and the wood fibre/ wood wool combination infills. These readings do not directly relate to wind-driven rain events and would therefore suggest interstitial condensation is occurring. Glaser calculations according to (BS EN ISO 13788:2012) (British Standards Institution, 2012) using the average internal and external temperatures for these period, confirm that interstitial condensation is likely due to the changes in water vapour diffusion properties within these constructions. More evidence of this can also be seen to be occurring at the horizontal junction between the panel infill and timber frame (Figure 5 and Figure 6)

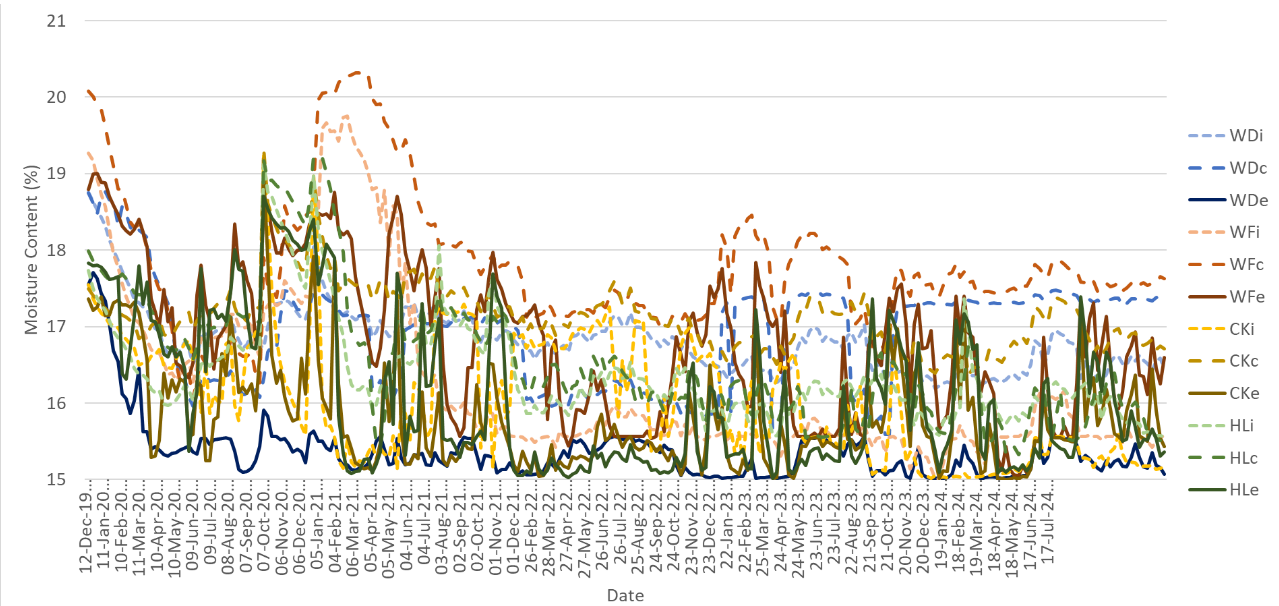

Figure 5. Wood Moisture Content at horizontal junction between NHL 3.5 finished panels and timber frame 12/12/2019 – 05/02/2025. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC-Hempcrete. i-internal, c-centre, e-external.)

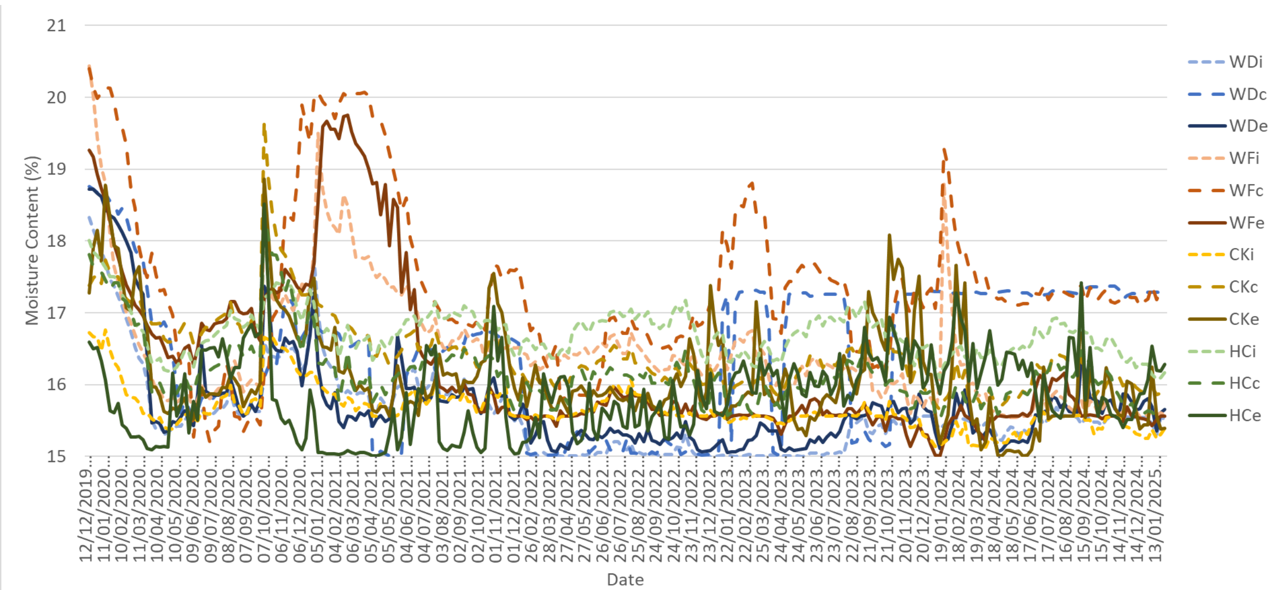

Figure 6. Wood Moisture Content at horizontal junction between Lime-Hemp finished panels and timber frame 12/12/2019 – 05/02/2025.

The high moisture content at this junction for the wood fibre/ wood wool detail had initially been thought to be due to the inclusion of an impermeable sealant. Whilst this may exacerbate the problem and increase drying times, the recent occurrence in the wattle & daub panels, which have no such sealant, suggest that interstitial condensation is the root cause. The fact that interstitial condensation is occurring in the most traditional material, wattle & daub may mean that our historic timber-framed buildings have always coped with these occurrences, or it may be a result of anthropogenic climate change and the increased occurrence of storm events. This would be an interesting area for future research utilising digital simulation using historic climate data and future climate predictions.

Overall, those panels finished in the more moisture permeable lime-hemp maintain a lower moisture content, with faster drying times.

Thermal Conductivity – Thermography

The external thermography (Figure 7- Figure 9) demonstrates the wattle & daub panels to be worst thermally performing, and the expanded cork the best. However, with the cork and wood fibre/ wood wool panels there is a large difference in surface temperature between infill and frame, with the frame forming a cold bridge. Internally this could be problematic, concentrating surface condensation on the historic fabric. The hempcrete, whilst not providing the same thermal efficiency, does create a more homogenous surface temperature and as such may provide less risk and be a more appropriate solution, especially for buildings of high heritage significance.

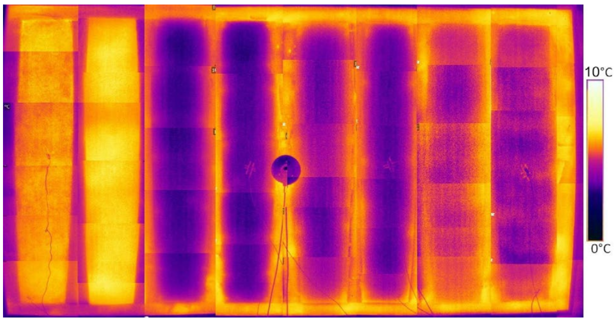

Figure 7. External thermography 07:00, 19/02/20. Internal temp. 20.6°C. External temp. 3.7°C

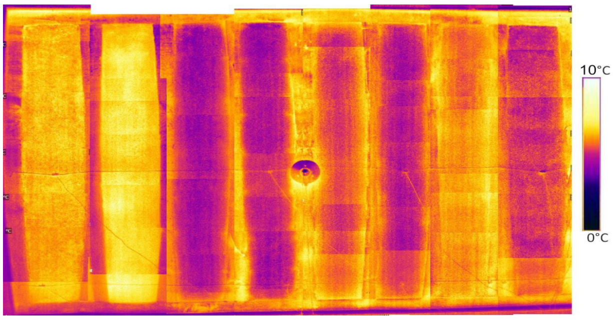

Figure 8. External thermography 07:00, 19/11/20. Internal temp. 20.5°C. External temp. 8.7°C

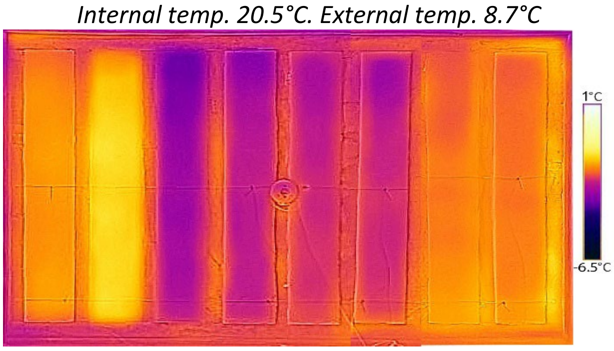

Figure 9. External thermography 07:00, 06/02/25. Internal temp. 20.5°C. External temp. 1.4°C

Thermal Conductivity – *in situ* U-value

Table 1: Results of in situ u-value measurements.

Infill Material	Finish	Position	Heating Season						Average
			2019/20	2020/21	2021/22	2022/23	2023/24	2024/25	
Wattle & Daub	NHL 3.5	Midpoint	2.92	2.95	2.65	2.13	2.98	2.28	**2.65**
		Corner	2.18	2.08	2.64	1.71	1.95	error	**2.11**
	Lime-Hemp	Midpoint	2.21	2.39	1.96	2.02	2.15	2.22	**2.16**
		Corner	2.40	2.39	2.11	1.87	1.35	2.16	**2.05**
Cork	NHL 3.5	Midpoint	0.54	0.50	0.52	0.65	0.61	0.62	**0.57**
		Corner	0.68	0.79	0.74	0.80	0.78	error	**0.76**
	Lime-Hemp	Midpoint	0.46	0.47	0.48	0.64	0.79	0.50	**0.56**
		Corner	0.53	0.53	0.47	0.44	0.52	0.57	**0.51**
Wood Fibre/ Wood Wool	NHL 3.5	Midpoint	0.71	0.63	0.64	0.65	0.55	0.61	**0.63**
		Corner	0.71	0.79	0.63	0.60	0.69	0.65	**0.68**
	Lime-Hemp	Midpoint	0.66	0.66	0.74	0.69	0.67	0.58	**0.67**
		Corner	0.77	0.84	0.85	0.81	0.72	0.72	**0.79**
Hempcrete	NHL 3.5	Midpoint	1.56	0.94	1.12	1.39	1.39	1.41	**1.30**
		Corner	1.54	1.30	1.48	1.35	1.30	1.49	**1.41**
	Lime-Hemp	Midpoint	1.22	0.99	1.39	1.59	1.54	1.34	**1.35**
		Corner	1.34	1.20	1.20	1.20	1.18	1.27	1.23

The results of *in situ* u-value measurements (Table 1) corroborate the external thermography and also show the improvement to thermal performance provided by the lime-hemp render with its insulating aggregate. Fluctuations in results year on year could be due to changes in moisture content; however, they are within the expected error factor, so may not be significant.

Discussion and Conclusion

This research highlights some of the key risks of retrofitting historic timber-framed buildings using replacement infill panels. Interstitial condensation is a risk where there are changes in material density and moisture permeability within the panel depth. Equally the use of infills with a thermal performance significantly better than the surrounding frame could focus internal surface condensation on the historic fabric. The use of moisture permeable materials, good detailing and installation are all paramount. Balancing these with the heritage values requires review on a case-by-case basis, and as noted, where intact historic infill exists, the solutions tested in this research would not be appropriate. The results do however demonstrate that in some cases, improvements to the energy performance of this historic construction typology are possible, increasing the potential for the continued habitation and use of these culturally important buildings.

It is hoped that the current digital simulation using measured material properties will produce results closer to those measured, enabling the simulation of both historic climate conditions and future predictions.

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References

Ballantyne, A. and A. Law 2011. Tudoresque and the Self-Reliant Englishman. In Guillery, P., *ed. Built from below : British architecture and the vernacular*, Abingdon, Oxon [England]; New York, NY, Routledge.

BEIS 2019. *UK becomes first major economy to pass net zero emissions law*. In Department for Business, E.a.I.S., *ed.*, UK Government. (29/10/20).

Braun, H. 1940. *The story of the English house.* London, B.T. Batsford.

British Standards Institution 2012. BS EN ISO 13788:2012 H*ygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods*. London, BSI.

British Standards Institution 2014. BS ISO 9869-1:2014 *Thermal insulation- Building elements- in situ measurement of thermal resistance and thermal transmittance Part 1: Heat flow meter method*. Lon., BSI.

Demaus, R. 2017. Insulation in Timber-framed Buildings. In Taylor, J., *ed. Special Report on Heritage retrofit.* The Building Conservation Directory.

Gailey, A. 1984. *Rural houses of the north of Ireland.* Edinburgh, Donald.

Harris, R. 2010. *Discovering Timber-Framed Buildings.* 3rd ed. Oxford, UK, Shire Publications.

Historic England 2017. *Energy Efficiency and Historic Buildings: Application of Part L of the Building Regulations to historic and traditionally constructed buildings* (Revised 2017). Historic England, UK.

Innocent, C.F. 1971. *The development of English building construction.* Newton Abbot, David and Charles.

McCaig, I. and B. Ridout 2012. *English Heritage practical building conservation- Timber.* London; Farnham, Surrey; Burlington, VT, English Heritage ; Ashgate.

Naismith, R.J. 1985. *Buildings of the Scottish countryside.* London, V. Gollancz in association with P. Crawley.

Nicol, S., C. Beer and C. Scott 2014. *The age and construction of English homes.* BRE.

OJEU 2018. *Directive (EU) 2018/844 of the European Parliment and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*. Official Journal of the European Union L156/75.

Whitman, C.J. 2017. *The distribution of historic timber-framed buildings in the UK and the impacts of their low energy retrofit*. Cardiff University.

Whitman, C.J., 2020. Building Performance Evaluation of a 14th Century Pargetted House: Hygrothermal comfort and energy efficiency. *Conference on Passive and Low Energy Architecture (PLEA), A Coruña, 1st-3rd September 2020: Proceedings* (pp. 294-299). Universidade da Coruña.

Whitman, C.J. and O. Prizeman 2016. U-value Monitoring of Infill Panels of a Fifteenth-century Dwelling in Herefordshire, UK. *APT Bulletin: The Journal of Preservation Technology*, **47**(4): 6-13.

Whitman, C.J., O. Prizeman, J. Gwilliam, A. Shea and P. Walker 2020. Energy retrofit infill panels for historic timber-framed buildings in the UK: physical test panel monitoring versus hygrothermal simulation. *Architectural Science Review*: 1-12.

Whitman, C.J., O. Prizeman, J. Gwilliam and P. Walker 2018. The impact of modernization of a 16th century timber-framed farmhouse, Suffolk, UK. *Energy Efficiency in Historic Buildings (EEHB) 2018*, Visby, Sweden