PLEA SANTIAGO 2022
Will Cities Survive?

Replacement Infill Panels for Historic Timber-Framed Buildings:

Measured and simulated hygrothermal behaviour

CHRISTOPHER J WHITMAN[1], ORIEL PRIZEMAN[1], PETE WALKER[2], SOKI RHEE-DUVERNE[3], IAIN McCAIG[4], NIGEL GERVIS[5]

[1] Welsh School of Architecture, Cardiff University
[2] University of Bath, [3] Historic England, [4] Formerly of Historic England, [5] Ty Mawr Lime Ltd

ABSTRACT: The historic built environment has a fundamental role to play in the future of our cities. It has been recognised to be instrumental in achieving social, economic, environmental, and cultural sustainability. However, operational carbon emissions must be reduced, and further research is required to achieve this. This paper presents the ongoing research by the authors, evaluating the energy retrofit of historic timber-framed buildings in the UK. The paper focuses on a funded research project where monitoring of replacement infill panels under real climatic conditions, and digital dynamic hygrothermal modelling, are utilised to determine the thermal performance of four infill materials, the hygrothermal conditions within and around the panels, and assess associated risk to the historic timber frame from moisture accumulation. The four materials monitored are traditional wattle-and-daub, expanded cork board, a composite detail of woodwool and wood fibre boards, and hempcrete. The results show wood fibre as the most susceptible to moisture accumulation. The use of impermeable perimeter sealants should be questioned; however, this requires further research. The results from simulations corroborated these main findings, however interstitial condensation was predicted at the inner face of the wood fibre insulation, which to date has not been measured. The monitoring is ongoing.

KEYWORDS: Heritage Retrofit, Hygrothermal Monitoring, Hygrothermal Simulation, Timber-Frame

1. INTRODUCTION

In the face of the current climate emergency, we are challenged to rethink the design of our cities and how we inhabit them. In the majority of cases the historic built environment constitutes a valuable component of our existing urban fabric. Its role has been recognised as fundamental in achieving social, economic, environmental, and cultural sustainability. It does this through the creation of social cohesion (CHCfE Consortium, 2015), and the strengthening of citizenship (United Nations, 2017). It forms the basis for vibrant, inclusive urban economies (ibid.), whilst at the same time it has been shown to promote wellbeing (Fujiwara et al., 2014). The continuing use of its embodied carbon reduces further carbon emissions that would otherwise result from new construction (Historic England, 2020), however, its operational carbon emissions must be reduced along with those of the rest of our existing building stock (IPCC, 2018). Given the technical and philosophical complexities of retrofitting heritage buildings and those of traditional construction, it has been identified that further research is required (OJEU, 2018). This paper focuses on the currently under-researched area of the energy retrofit of historic timber-framed buildings in the UK. The paper will begin by outlining this building typology and the opportunities and challenges faced when aiming to improve its energy efficiency. It will then introduce the methodology and results for a specific experiment that has been undertaken to examine the performance and associated risks of four potential replacement infill panels. Measurements from the physical monitoring are compared to the results of digital dynamic hygrothermal simulation.

2. HISTORIC UK TIMBER-FRAMED BUILDINGS

Timber-framed buildings hold a special place in the cultural identity of the UK and more specifically England (Ballantyne & Law, 2011). With their structural frame commonly exposed both internally and externally (fig.1), these buildings have become synonymous with “Olde England” and as such have been emulated around the world (ibid.). The exposed frame was most commonly traditionally infilled with wattle-and-daub (earthen render on a woven timber lattice), although other historic infill materials such as lath and plaster, brickwork, and stone can be found (Harris, 2010). Today there are approximately 68,000 nationally designated heritage assets, built before 1850, of this typology (Whitman, 2017). Of these, 70% are dwellings and a further 14% are in use as commercial premises (ibid.). As such, the need to reduce their energy demand and increase internal hygrothermal comfort is critical.

Figure 1:
C15 timber-framed building, Lavenham, UK, showing exposed structural frame. (Lead Author, 2017)

2.1 Retrofit of historic timber-framed buildings

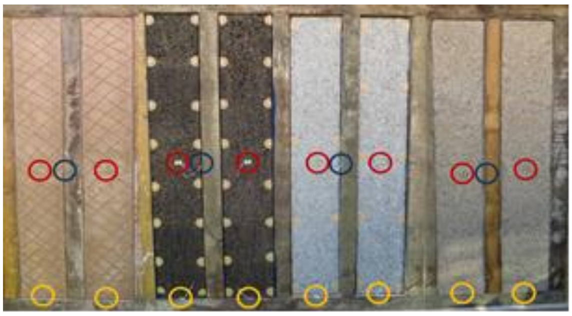
Given that the exposed frame (fig.1) is a defining part of these building's aesthetic heritage value, the energy retrofit options for their walls are limited. Nevertheless, where the historic infill panels are beyond repair, or have already been replaced, an infill material with a higher thermal resistance may be retrofitted (Oxley, 2010). However, changes to the hygrothermal performance of the infill panel may affect that of the surrounding historic fabric, raising the risk of interstitial condensation, moisture accumulation and the creation of conditions ideal for fungal decay and insect infestation. The junction between the infill material and the exposed frame presents a particular challenge in achieving airtightness and preventing water ingress. Consideration of the design of this detail, in conjunction with experienced workmanship is therefore critical to the success of the whole intervention.

3. METHODOLOGY

The research presented in this paper builds on previous research by the authors (Whitman et al., 2018, Whitman et al., 2020). To address the difficulties of undertaking *in situ* monitoring within historic walls at case study properties, and the limitations of laboratory testing, the decision was taken to monitor physical test panels exposed to real climatic conditions over an extended period (a minimum of 18 months). The panels were mounted in the north façade of a test cell located in Cardiff, Wales, UK, with the external face of the panels exposed to the Cardiff climate, and the internal environment heated (21°C) and humidified (≥60%) during the UK heating season (Nov.-Mar.). Outside of these dates, the internal conditions were free running, replicating the reality in most UK homes. The external climate (temp. (°C), RH (%), precipitation (mm), air pressure (mbar), wind speed (m/s) and wind direction) was measured using a Vaisala WXT520 mounted on the roof of the test cell. Following the failure of the integrated electronic rain gauge early in the project, this was replaced after two months with a 52202 tipping bucket rain gauge manufactured by R.M. Young. Direct solar radiation (W/m2) incident on the panels was measured using a Kipp and Zohnen® CM5 pyrometer, and the internal temperature (°C) and RH (%) of the cell with a Campbell Scientific® CS215. All sensors were wired to a Campbell Scientific® CR1000 data logger.

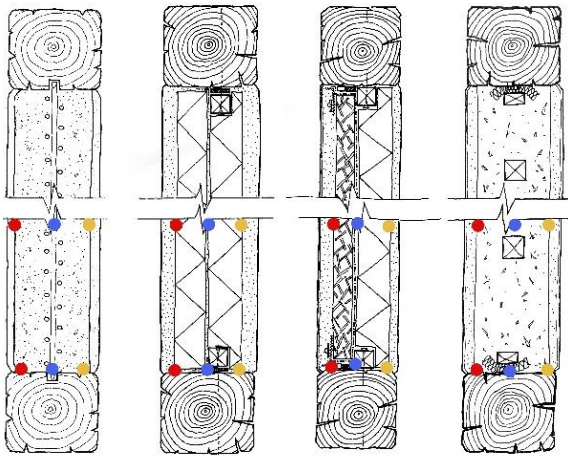
The dimensions of the panels were defined by a review of 100 historic timber-framed buildings, resulting in a typical panel size of 305 mm wide by 1830 mm high. Four different infill materials monitored were monitored (fig 2), wattle-and-daub, expanded cork board, a composite detail of woodwool and wood fibre boards (McCaig & Ridout, 2012), and hempcrete (Stanwix & Sparrow, 2014). Pairs of panels were constructed within reclaimed oak frames, with one of each finished in a render based on Natural Hydraulic Lime (NHL) 3.5 and the other in a non-hydraulic lime render with hemp shives as an aggregate (lime-hemp).

Figure 2:
Test panels prior to application of external render. Infill materials Left to right- wattle and daub, cork, wood fibre/wood wool, and hempcrete. Monitoring positions highlighted, red- centre panel, blue- vertical frame/panel junction, and yellow-horizontal frame-panel junction (Lead Author, 2019)



The thermal performance of the panels was assessed January-March 2020, and repeated November 2020-January 2021 and again November 2021-February 2022. This was undertaken using *in situ* U-value measurements according to BS ISO 9869-1:2014. Thermography following best practice guidelines (Young, 2015) was also undertaken on the 19th February 2020 and the 19th November 2020 both at 07:00, 30 minutes prior to sunrise to minimise the impact of direct solar radiation on the façade and maximise the internal/external temperature difference. Interstitial hygrothermal conditions were monitored continuously from December 2019 to December 2021 using Type T thermocouples (°C) and electrical resistance for moisture content (%). The monitoring positions as highlighted in figure 2 were located at the centre of each panel, at the horizontal junction at the base of each panel, and halfway up the vertical junction of the panels finished in NHL3.5 based render. At each position, sensors were placed at three depths (fig 3): between the internal plaster and insulation, at mid-depth, and between the insulation and external render. The sensors were wired back to the CR1000 data logger, with measurements at 30-minute intervals.

Figure 3:
Sections showing panel infill details and monitoring locations. Materials left to right- wattle and daub, cork, wood fibre/ wood wool and hempcrete. Monitoring locations Red- external (e), Blue- central (c), and Yellow- internal (i).



Following 18 months of monitoring, the measured climatic data was used to undertake dynamic hygrothermal simulations using WUFI® Pro 5.3 software and the measured and simulated results compared. Analysis of the material databases pre-existing within WUFI® Pro 5.3 (Fraunhofer Institute, 2013) was undertaken to assist with the selection of materials assigned to the components in the simulation. However, it should be noted that only in the case of the wood fibre insultation was this a precise match for the material, manufacturer, and product of the physical construction. For all other components a closest match was chosen. This was based only on limited material property data for the real materials. Additional funding is currently being sought to undertake detailed material characterisation of all materials used in the physical test panels to further improve this element of the research.

4. RESULTS

4.1 Thermal Performance

The *in situ* U-value measurements of the 103mm thick panels are presented in table 1. These show that the cork infill achieves the best thermal performance with an average U-value of 0.52W/m^{2}K for the panels finished in the NHL 3.5 based render and 0.47W/m^{2}K for the lime-hemp render. The worst thermal performance is seen from the wattle-and-daub with averages of 2.84W/m^{2}K (NHL 3.5) and 2.19W/m^{2}K (lime-hemp). Overall, the use of the lime-hemp render achieves an average 10% improvement in U-value.

Table 1. *U-values of test panel measured at centre of each 103mm thick panel according to BS ISO 9869-1:2014. For the periods Jan.-Mar. 2020 (A), Nov. 2020 – Jan. 2021 (B) and Nov. 2021-Feb 2022 (C) and average (Av.)*

Infill Material	Plaster	U-Value (W/m^{2}K)			
		A	B	C	Av.
Wattle & Daub	NHL	2.92	2.95	2.65	2.84
	LH	2.21	2.39	1.96	2.19
Cork	NHL	0.54	0.50	0.52	0.52
	LH	0.46	0.47	0.48	0.47
Wood fibre	NHL	0.71	0.63	0.64	0.66
	LH	0.66	0.66	0.74	0.69
Hempcrete	NHL	1.56	0.94	1.12	1.21
	LH	1.22	0.99	1.39	1.20

NHL- Natural Hydraulic Lime 3.5 and LH-Lime-hemp

It had been hoped to see an improvement in the thermal performance of all panels, especially those with wet applied infill materials (wattle and daub, and hempcrete), as the panels dried out. There was however only a minimal difference in moisture content within the panels (>2%) between each of the three rounds of U-value measurements due to climatic conditions. The Hempcrete panels show an improvement in thermal performance over the first year despite displaying similar moisture contents, however this improvement is reversed by the time of the final U-value being measured. None of the U-values for this material meet the U-values of 0.67W/M^{2}K (NHL) and 0.58W/M^{2}K (LH) predicted based on literature for this construction technique.

Thermography (fig 4 and fig 5) undertaken in the conditions as noted in table 2, verified the results of the *in situ* U-value measurements.

Table 2: *Dates and conditions of thermography*

Date	Time	Int. Temp. (°C)	Ext. Temp. (°C)
19/02/20	07:00	20.6	3.7
19/11/20	07:00	20.5	8.7
Difference		-0.1	+5.0

Figure 4*:*
External thermography 07:00, 19/02/20. Internal temp. 20.6°C. External temp. 3.7°C. NHL- Natural Hydraulic Lime 3.5 and LH-Lime-hemp

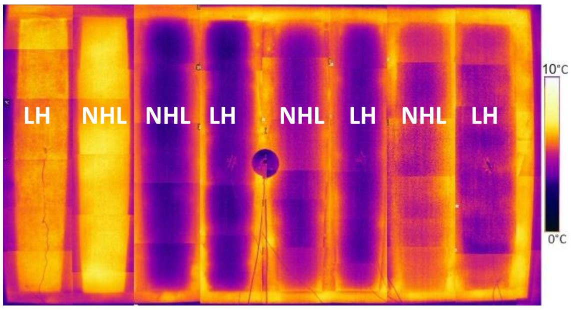
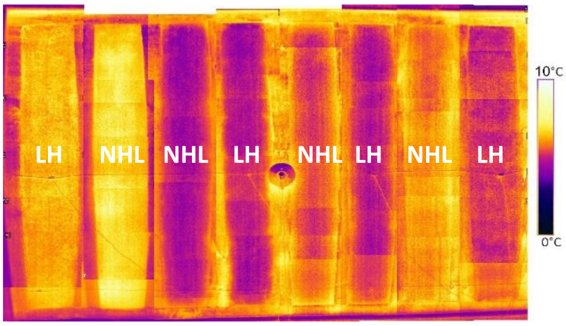


Figure 5:
External thermography 07:00, 19/11/20. Internal temp. 20.5°C. External temp. 8.7°C



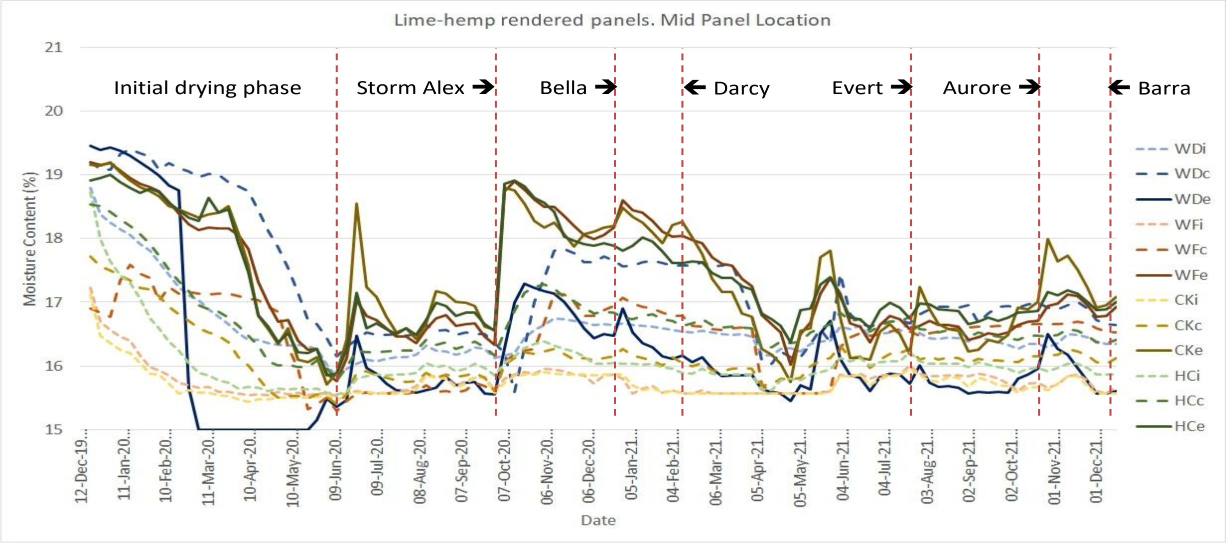
4.2 Moisture Content

The moisture content monitoring showed an initial drying period of approximately six months following construction for most monitoring positions. However, for the monitoring positions at the horizontal junction between infill and timber frame, those materials finished in lime-hemp render dried two months earlier than those finished in the NHL 3.5 based render.

This difference in drying times may be explained by the greater moisture permeability of the lime-hemp plaster. However, this would not explain why this was only detected at the horizontal junction and not at any other monitoring position. At all other positions no discernible difference in drying times was noted between panels finished with the two different renders.

These initial drying periods were then followed by a series of wetting and drying cycles (fig 6). As these cycles correspond exactly to climatic conditions, principally related to wind-driven rain during named storm events, it can be concluded that no evidence of interstitial condensation has been measured to date. Over the 18 months of monitoring a total of six named storm events took place, each with a varying degree of impact on the moisture content of the panels and timber frame. The largest impact was experienced following Storm Alex during which the wettest day since records began in 1891 was recorded in the UK (Met Office, 2020). It should be noted that at the time of the design of this experiment the frequency and intensity of these storm events was not foreseen. Although not a planned objective, the results have demonstrated the impact of such storms on the moisture content of timber-framed building elements. Climate change predictions anticipate an increase in major storms (IPCC, 2018) and as such further research is recommended into the implications of this for timber heritage in the UK and beyond.

Figure 6:
Moisture Content Measurements 12/12/2019 – 22/01/2021. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC-Hempcrete. i-internal, c-centre, e-external.) Showing major increases in moisture related to storm events.



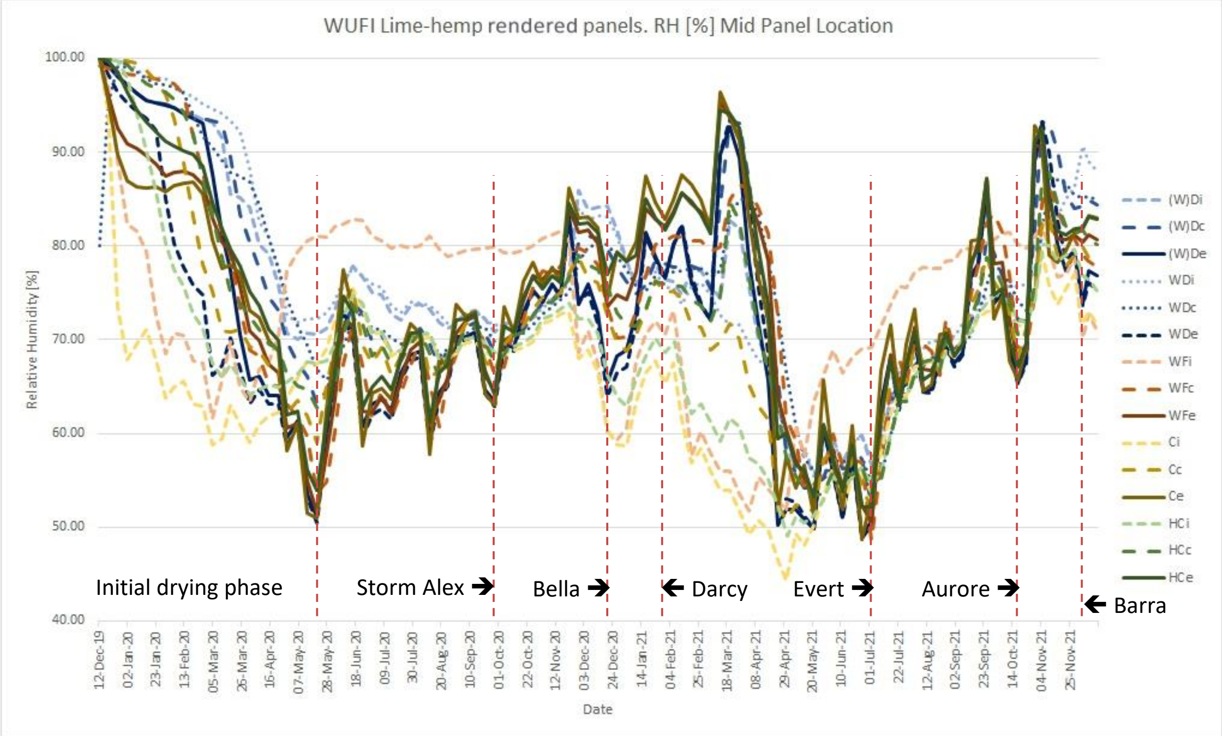
As a consequence of Storm Alex, the results from the monitoring positions at the horizontal junction between infill panel and timber frame showed a rapid increase in moisture content within the wood fibre/wood wool panels, both for those finished in the lime-hemp render and the render based on NHL 3.5. The highest moisture content was recorded at the mid-depth of these panels at this junction, with this exceeding 20% for three months and remaining over 18% for over a year. A lesser increase was also seen at the same time in the moisture content at the vertical junction for the cork infill panels, however this remained over 18% for only four months. For both these infill materials (wood fibre/wood wool, and cork) the recommended installation detail included an impermeable sealant around the perimeter. This would potentially appear to trap moisture entering the joint through capillary action. Further investigation of this is required.

4.3 Digital dynamic hygrothermal simulation

The results of the WUFI® Pro 5.3 simulations were plotted and compared with those measured. As the software package does not generate moisture content for specific monitoring positions, only for material layers, relative humidity (RH%) has been plotted as a proxy. Whilst this does not allow direct numerical comparison, it does allow profiles to be compared (fig 7.). In general, although the profiles are not exact matches, the simulations did corroborate the measured results, indicating the major changes in moisture content to result from wind-driven rain. However, they also predicted an increase in moisture content at the internal face of the wood fibre insultation which appears unrelated to any wind-driven rain, predating the first storm event. This would suggest a prediction of interstitial condensation within this construction. As previously noted, this has not been measured to date. The other notable difference between simulations and measured results is that the simulation does not demonstrate the same spread of results for the different infill materials and monitoring positions measured in reality.

WUFI® 2D simulation was attempted for the junction between the infill panels and timber frame, however the results were inconclusive and are not included in this paper.

Figure 7:
Results of WUFI® Pro 5.3 simulation for Lime-Hemp rendered panels mid panel monitoring location. (WD-Wattle & Daub, WF-Wood Fibre, CK-Cork, HC- Hempcrete. i-internal, c-centre, e-external.)



5. CONCLUSION

The results show that use of cork, hempcrete and wood fibre can significantly improve the thermal performance of infill panels for historic timber-frame buildings, especially when coupled with lime-hemp finishes. Of these, the composite detail of woodwool and wood fibre boards would appear the most susceptible to moisture accumulation. The digital dynamic simulation has suggested that interstitial condensation may also be an issue for this retrofit detail, however this has as yet not been proven by the measured data.

The increase in moisture content measured at the horizontal, and to a lesser extent vertical, junctions between infill material and timber frame suggests that the use of impermeable sealants should be questioned; however, this requires further research. The role of experienced workmanship is most probably as important as the materials utilised at this critical junction, and the need for achieving airtightness is still essential for the overall thermal performance of the assembly.

The impact of wind-driven rain occurring as a result of storm events, although not anticipated, is a key finding of this research. The predicted increase in such events created by anthropogenic climate change will unfortunately create less favourable conditions for these historic buildings with or without retrofit. This is true for much of our historic built environment but may be more critical for our timber heritage. This highlights an important area for further research. Funding has recently been received for a further two years of monitoring and the authors continue to work on pursuing other related investigations.

ACKNOWLEDGEMENTS

The research covered in this paper has been made possible by Historic England funding. The authors also wish to thank Royston Davies Conservation Builders for the construction of the test cell, Hempcrete UK for the materials and construction of the hempcrete panels and Ty Mawr Lime Ltd for most of the other materials.

REFERENCES

Ballantyne, A., & Law, A. (2011). Tudoresque and the Self-Reliant Englishman. In P. Guillery (Ed.), *Built from below : British architecture and the vernacular*. Routledge.

CHCfE Consortium. (2015). *Cultural heritage counts for Europe. Full report*. https://www.europanostra.org/our-work/policy/cultural-heritage-counts-europe/

Fraunhofer Institute. (2013). *WUFI Pro 5.3*.

Fujiwara, D., Cornwall, T., & Dolan, P. (2014). Heritage and wellbeing. *Historic England*.

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

Historic England. (2020). *Heritage Counts: There's no place like old homes. Re-use and Recycle to Reduce Carbon*. https://historicengland.org.uk/research/heritage-counts/2019-carbon-in-built-environment/carbon-in-built-historic-environment/

IPCC. (2018). *Global Warming of 1.5 ºC*. https://www.ipcc.ch/sr15/

McCaig, I., & Ridout, B. (2012). *English Heritage practical building conservation- Timber*. English Heritage ; Ashgate.

Met Office. (2020). *Record Breaking Rainfall for October* https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2020/mid-october-statistics

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* (L156/75). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN

Oxley, P. (2010). *Insulating timber-framed walls* (D. Pickles, I. Brocklebank, & C. Wood, Eds.). English Heritage. http://www.climatechangeandyourhome.org.uk/live/content_pdfs/781.pdf

Stanwix, W., & Sparrow, A. (2014). *The Hempcrete Book Designing and Building with Hemp-Lime*. UIT Cambridge Ltd. http://public.eblib.com/choice/PublicFullRecord.aspx?p=1811266

United Nations. (2017). *New Urban Agenda*.

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., Prizeman, O., Gwilliam, J. & Walker, P. (2018) The impact of modernization of a 16th century timber-framed farmhouse, Suffolk, UK. The 3rd International Conference on Energy Efficiency in Historic Buildings (EEHB2018), Visby, Sweden, September 26th to 27th, 2018. Uppsala University, 182-190.

Whitman, C. J., Prizeman, O., Gwilliam, J., Shea, A. & Walker, P. (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.

Young, M. (2015). *Thermal Imaging in the Historic Environment* (Short Guide, Issue. https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=088dab34-1194-43e6-af5e-a62801090992