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Energy Retrofit Infill Panels for Historic Timber-Framed Buildings in the UK: Physical test panel monitoring versus hygrothermal simulation

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As we aim to decarbonise the built environment, care must also be taken to minimise the negative impact of retrofit actions on historic buildings' fabric and cultural significance. Work to date in the UK has focused on the retrofit of historic solid masonry construction, with little research into historic timber-framed buildings. With these buildings, where infill panels are beyond repair or have previously been substituted with inappropriate materials, there exists the potential to retrofit panels with a higher thermal performance. The research presented in this article compares the monitoring of three physical test panels mounted between climate-controlled chambers with digital hygrothermal simulations in order to investigate the risk of increased moisture which may threaten the surrounding historic fabric. Results of previously unpublished cyclical testing are is also included. Whilst all prediction methods successfully identified interstitial condensation where measured, major discrepancies existed between simulated and measured results, and between different simulation methods.

Keywords: timber-framed; hygrothermal simulation; hygrothermal monitoring; interstitial condensation; energy retrofit; historic built environment

Introduction

With the 2018 Amended Energy Performance of Buildings Directive, the European Union has declared its aim of decarbonising the built environment by 2050 (OJEU 2018). The Directive specifically calls for research into solutions for historic buildings, recognising the need to balance the energy performance of these buildings with the safeguarding of their cultural heritage (ibid), in addition to achieving occupant comfort and assuring indoor air quality. Care should therefore be taken to minimise negative impacts and avoid damage to the building's significance, character and fabric (Historic England 2017). A key consideration is the influence of thermal insulation on the hygrothermal performance of the external envelope, where increases in moisture content arising from interstitial condensation could adversely affect the pre-existing historic materials. Research in the UK has so far focused on the impact of insulation on solid masonry construction (Gandhi, Jiang , and Tweed 2012; Rye, Scott, and Hubbard 2013; Baker 2015) with little investigation into the retrofit of the 68,000 historic timber-framed buildings (Whitman 2017) which form an important part of Britain's cultural identity.

Retrofitting Historic Timber-Framed Buildings in the UK

Historic timber-framed buildings in the UK consist of a structural timber frame with a solid infill. This is traditionally wattle-and-daub, a framework of thin timber members (wattlework) covered by an earthen render (daub). Other historic infills include lath and plaster and brick nogging (Harris 2010). Whist some of these buildings are over-clad with tiles, weatherboarding or continuous plaster, in many cases the timber frame is exposed both internally and externally (Figure 1 & Figure 2).

Figure 1. Externally exposed frame. (Whitman, 2015)

Figure 2. Internally exposed frame. (Whitman, 2015)

When retrofitting these buildings, in order to retain the aesthetics and character of the building, the exposed framing often precludes the use of internal and / or external wall insulation. This leads to problems created by the thermal bridging of the frame, potentially focusing interstitial condensation at the junction between the infill panel and the timber-frame. In addition, achieving a seal at this junction is often problematic, leading to issues with moisture ingress and poor airtightness (Whitman and Prizeman 2016).

Work to any historic building in the UK should follow a set of ethical principles as set out by each of the four national governmental bodies related to heritage, Historic England (Historic England 2008), Cadw (Cadw 2011), Historic Environment Scotland (Historic Environment Scotland 2016) and the Northern Ireland Department for Communities, Historic Environment Division (Historic Environment Division 2017). In general, it is expected that where possible, every effort will be made to retain existing historic fabric, and where replacement is required that this normally takes place on a "like-for-like" basis (Historic England 2008). It is, however, accepted that this is not always possible or the best option. For example, where historic infill is beyond repair, has been replaced with inappropriate modern materials, or its removal is required to facilitate the repair of adjacent timbers, there exists the opportunity to retrofit an infill material with a higher thermal resistance (Oxley 2010). For this article the performance of three infill materials was compared.

The UK Building Regulations state that designated historic buildings are exempt from their energy efficiency requirements, insofar as compliance would "unacceptably alter the appearance or character of these buildings" (HM Government 2016). This exemption is further extended to those buildings of traditional construction with permeable fabric, such as historic timber-framed buildings, where work should not "increase the risk of long-term deterioration of the building fabric or fittings" (ibid). However, in both these cases the regulations do require that the "aim should be to improve energy efficiency as far as is reasonably practicable" (ibid.). As such the extent and detail of the energy retrofit of these buildings remains at the discretion of the building owner in consultation with design professionals, building control and conservation officers. This highlights the need for quality, research-based guidance and best practice documents.

UK research on retrofit of historic timber-framed buildings

Prior to the work of the authors, in the UK there would appear to be almost no academic research into the retrofitting of historic timber-framed buildings. Whilst some research has been undertaken in France (Valkhoff 2011) and Germany (Gerner 2000; Dederich, Koch, and Fischer 2004) which is still relevant, little specific research involving the UK climate and local materials and construction techniques would appear to exist.

The Prince's Regeneration Trust's book "The Green Guide for Historic Buildings," (Prince's Regeneration Trust 2010) and Martin Godfrey Cook's book, "Energy Efficiency in Old Houses" (Cook 2009) both contain the same case study, Berg Cottage, Barkway, Hertfordshire (Prince's Regeneration Trust 2010, p.27-28; Cook 2009, p.42-45). This cottage is one of the few case studies of the retrofit of a historic timber-framed building in the UK where monitoring has been undertaken post-retrofit. The same cottage appears again briefly in the Energy Savings Trust's "Energy Efficiency Best Practice in Housing Advanced insulation in housing refurbishment" (Energy Saving Trust 2005, p.22) and photos of it are featured in Historic England's guidance on insulating timber-framed walls (Historic England 2016). Although the description in all sources is quite brief, the case study does include details of pressure testing, with 24 air changes per hour at fifty pascals(ac/hr@50 Pa) measured pre retrofit (Cook 2009, p.44) and at 16 ac/hr @ 50 Pa post-retrofit (Energy Saving Trust 2005, p.22). The case study includes the introduction of external sheep's wool insulation behind weatherboarding, which achieved a reported reduction in gas consumption of 27% (Prince's Regeneration Trust 2010, p.28) and a reduction in overall fuel consumption by 50% (Cook 2009). It should however be noted, that being externally weatherboarded, this case study does not address those issues timber-framed buildings with their frame exposed externally.

In addition the first SPAB U-Value report (Rye, Scott, and Hubbard 2012a), the research undertaken by Archimetrics did include a two timber framed-buildings, however neither went on to be retrofitted and covered by the subsequent "SPAB Building Performance Survey" (Rye, Scott, and Hubbard 2012b, 2013; Archimetrics Ltd 2014, 2015, 2017).

In order to address this lack of UK research, the authors have conducted in situ monitoring at a number of case studies (Whitman and Prizeman 2016; Whitman et al. 2018; Whitman et al. 2019). At one case study it was possible to undertake opening up and interstitial measurements (Whitman et al. 2018) which showed that unfortunately, favourable conditions for biological attack were being created. A key factor was that the replacement infill panel detail did not follow current best practice guidelines, using both vapour impermeable insulation and finishes. In this instance the use of rigid board insulation and gypsum plasterboard made the installation of interstitial sensors possible with minimal disruption to the construction. This would, however, be difficult to replicate in many other instances, where the required intervention could damage historic fabric, whilst at the same time potentially significantly alter the hygrothermal performance of the element under review. As such, the authors have also undertaken digital simulations (Whitman, Prizeman, and Walker 2015). These suggested that for the specific climate conditions simulated, none of the replacement infill panel details currently included in best practice guidance (Reid 1989; McCaig and Ridout 2012; Oxley 2010), posed a serious increase in the risk of biological attack. However, due to the limitations of both the software and available material data, the research concluded that physical monitoring was essential.

Aims and Objectives

The work presented in this article aims to establish the risk of interstitial condensation and increased moisture content within replacement infill panels for timber-framed buildings, and the risk posed to surrounding historic fabric. In order to achieve this, measured results from panels mounted between two climate-controlled chambers have been compared with those obtained through hygrothermal simulation. This has allowed the assessment of three potential replacement infill panel details and the evaluation of the use of numerical modelling for the assessment of this type of construction.

Methodology

There follows the methodologies for the selection of the infill materials to be evaluated, the design and monitoring of the physical test panels and the hygrothermal simulations undertaken.

Test Panel Infill

A longlist of potential infill panels was identified following a literature review of current advice from Historic England (McCaig and Ridout 2012; Pickles 2016) and the Society for the Protection of Ancient Buildings (SPAB) (Reid 1989), and other authors both historic (Charles 1967) and contemporary (Suhr and Roger 2013; Stanwix and Sparrow 2014; Valkhoff 2010), in addition to discussion with conservation practitioners and suppliers of insulation materials for conservation projects. The replacement infill panels identified are summarized in Table 1:

Table 1. Panel infill materials identified through literature review

Age of Infill Detail	Principal materials	Description	Estimated U value* for 100mm (W/m^2K)
Traditional	Wattle and Daub	Clay based render on a supporting network of woven small section timber members.	2.83
	Oak lath and lime plaster	Lime plaster/render on supporting background of thin strips of oak with central uninsulated cavity.	2.07
	Brick noggin	Fired bricks	3.35
	Stone	Varies according to regional availability	4.31
Mid-to late-20th Century	Rendered woodwool boards	Rigid boards of compressed wood strands with cementitious binder.	0.97
	Rigid insulation boards with cement render on expanded wire mesh	Insulation boards include woodwool, expanded polystyrene, rockwool batts and Polyisocyanurate (PIR).	0.30-0.51
	Rock- or glass-wool quilt	Rendered with cement render on expanded wire mesh	0.56
	Lightweight concrete blocks		1.68
Late 20th Century – 21st Century	Hemp/lime	Mixture of hemp shives and a lime binder, also known as hempcrete	0.84
	Light-earth (leichtlehm)	A mix of straw and earth or clay binder	0.83
	Cellulose fibre		0.72
	Sheep’s wool insulation	Insulation held within oak lath and lime plaster	0.62
	Woodfibre insulation	Finished externally with lime plaster on woodwool carrier board	0.42

	Cork insulation	Expanded cork board finished internally and externally with lime plaster.	0.48

* Estimated U-values calculated with Rsi and Rse as per BS 6946:2007 (British Standards Institution 2007)

Considering issues of breathability, built-in moisture content, buildability and environmental impact, a short list of five replacement infill panel solutions were chosen. These were traditional wattle and daub; wood-fibre insulation with lime plaster on woodwool carrier board (McCaig and Ridout 2012); Cork insulation with lime plaster (Ty Mawr Lime Ltd. 2015); hemp-lime (Stanwix and Sparrow 2014); and sheep's wool (Prizeman 2015). Of these the first three were chosen to monitor due to the lack of available material data, required for digital simulation, for the last two infill solutions. Details of the three chosen build-ups are shown in Figure 3.

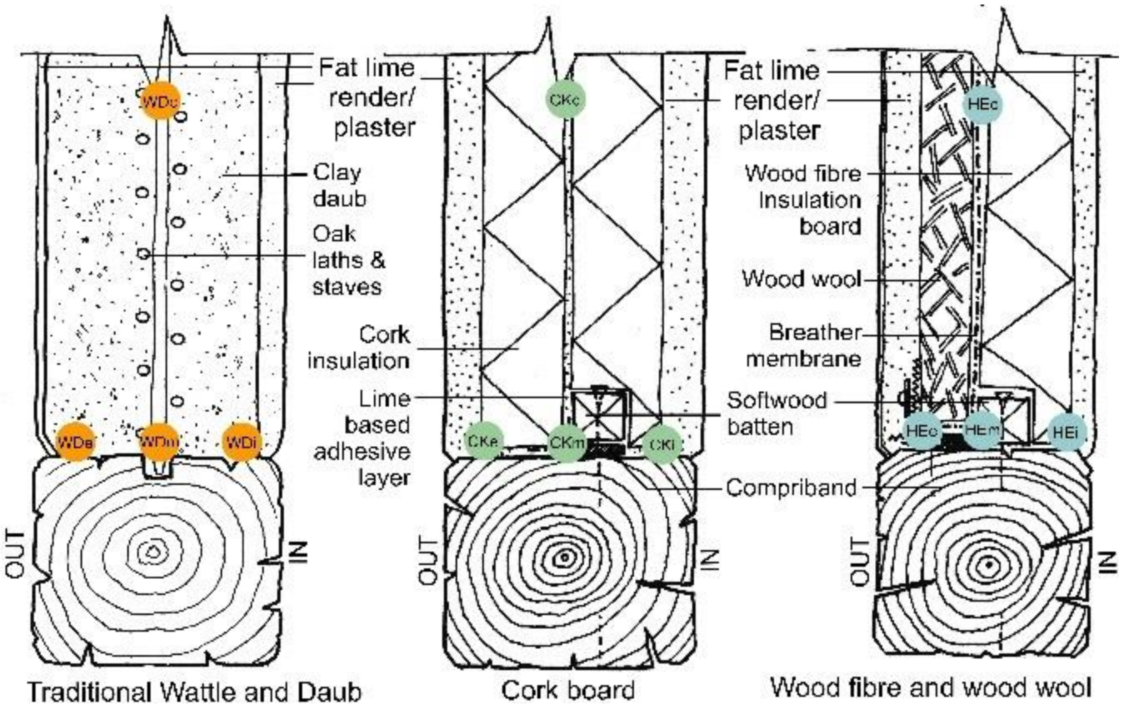

Figure 3. Detailed sections of three panel infill build-ups showing monitoring positions

Physical Test Panels

In order to physically measure the hygrothermal performance of these three construction details, three test infill panels 820mm x 820mm x 100mm (L x W x D) were constructed within oak frames constructed from reclaimed oak.

Definition of Test Panel Dimensions

The dimensions of the panels were dictated by the test facility, however a review of a representative sample of 100 surviving UK timber-framed buildings was undertaken to establish the average infill panel size for comparison. It was assumed that all historic (pre-1850) timber-framed buildings are designated as listed buildings. Therefore a dataset was requested from Historic England searching the National Listings using the search parameters "Pre-1850, Timber Framed Building; Jettied Building; Jettied House; Continuous Jetty House; End Jetty House; Wealden House; Single Ended Wealden House; Timber Framed Barn; Cruck Barn; Timber Framed House; Box Frame House; Cruck House; Base Cruck House" (Historic England 2014). The resulting dataset of 66,397 entries was reviewed and classified according to age, building type (domestic, commercial/public or ancillary) and panel infill material. Buildings listed as "former timber-frame" and those subsequently entirely encased within a continuous masonry envelope were deleted. List entries covering multiple buildings were duplicated to create one entry per building. The resulting dataset contained 66,801 buildings. A similar exercise was completed for Wales using Peter Smith's "Houses of the Welsh Countryside" (Smith 1988) updated with information from Richard Suggett's "Houses and History in the March of Wales: Radnorshire 1400-1800" (Suggett 2005) and cross-referenced with the National Monuments Record of Wales (RCAHMW 2014). The Welsh dataset resulted in 1023 buildings. Both datasets were subsequently plotted using ArchGIS™ 10.5.1 geographic information system.

A sub-dataset was then created including only those buildings where the timber-frame was externally exposed and therefore visible for measurement. Externally plastered, weather-boarded, tile-hung and slate-hung buildings were therefore excluded. A representative sample of 100 buildings was then selected. These proportionally represented the exposed timber-framed buildings with regards to age, building type, panel infill material and geographical location (Figure 4). Using Google Streetview^{TM}, photos were collected of each of these 100 buildings. These were then scaled and measured in AutoCAD. The measurements were then plotted and the averages taken (Figure 5).

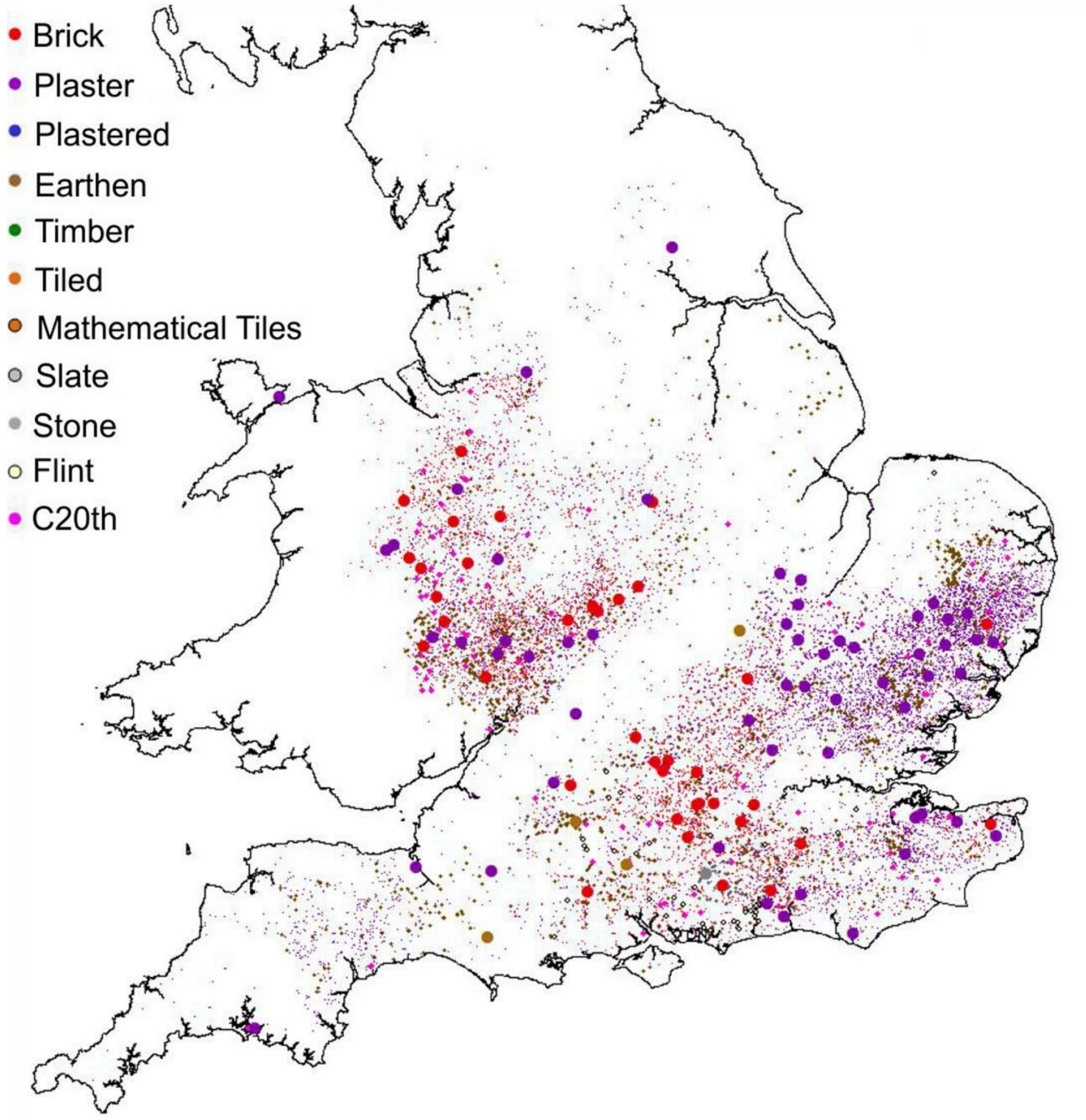

Figure 4. Distribution of timber-framed buildings in England and Wales (small dots) and 100 representative samples (larger dots). Source: Authors' own based on (Historic England 2014; Smith 1988; Suggett 2005; RCAHMW 2014)

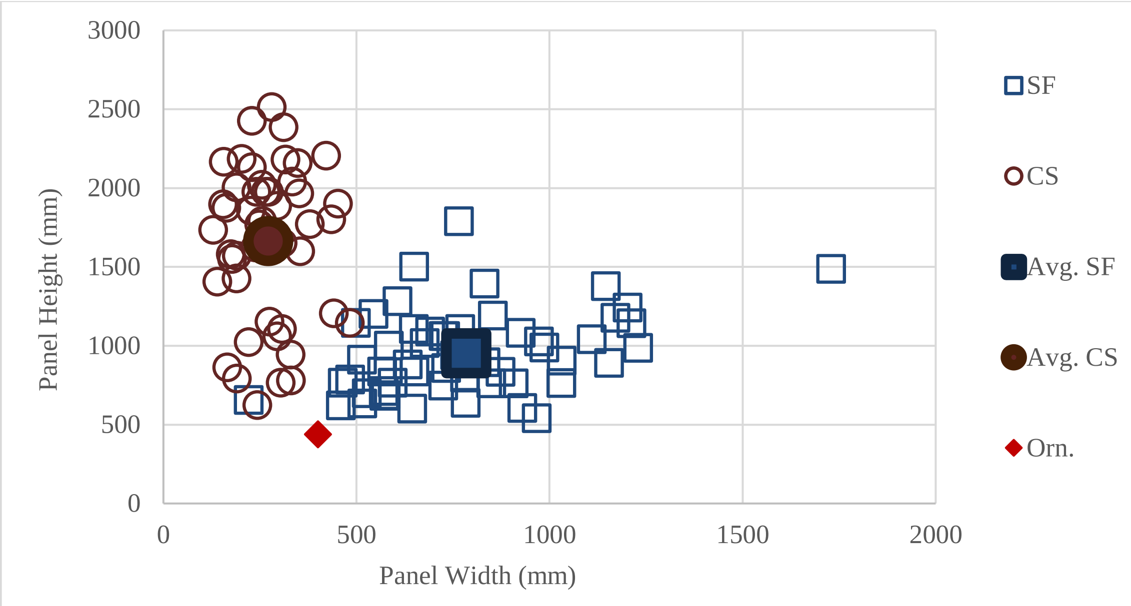

Figure 5. Dimensions of 100 representative sample infill panels. Square Framed (SF), Close Studded (CS), Ornamental (Orn).

The results indicate that 53% were “square framed”, 46% “close studded” (tall rectangular panels) and 1% “ornamental”. The average dimensions of the square framed panels were 785mm x 950mm (L x W) with a standard deviation of ±260mm. As such, the test panels of 820mm x 820mm x 100mm (L x W x D) can be said to be representative in size.

At the same time the width of the exposed timber frame was measured on the same data set. This showed an average width of 106mm, with a standard deviation of ±52mm. Although slightly thinner than average, the oak frame for the test panels, with a width of 80mm can still be said to be representative.

Age of Surrounding Timber-Frame

Given that the test panels aim to represent new infill panels within existing historic timber-framing, the question arose as to the potential differences in hygrothermal behavior of modern and historic oak. A key factor would be any notable effect of age on the timber’s moisture sorption properties. In order to investigate this possibility, Dynamic Vapor Sorption (DVS) analysis was undertaken on three 10mm cubes of oak felled in the 17^{th}, 19^{th} and 21^{st} centuries. The analysis was undertaken by Surface Management Systems Ltd using their DVS-Advantage instrument. The samples were initially dried for 600 minutes under a continuous flow of dry air to establish their dry mass. The samples were then exposed to the following typical partial pressure (vapour pressure/ saturation vapour pressure (p/po)) profile: 0% to 40% p/po in 5 % steps, then to 90% p/po in 10% step increments, and then a 5% step to 95% p/po and then decreased in a similar manner (Demonstration & Contract Testing Services 2015). The instrument measured the mass of each sample throughout this process and provided results as percentage change in mass against percentage relative humidity. The results are presented in Figure 6. This shows that the older timber absorbs less moisture overall. It also shows a maximum hysteresis for each sorption curve (absorption against desorption) of 3.7%, 4.0% and 3.4% in order of age. It was therefore concluded that for the test cell historic reclaimed timbers should be sourced as opposed to newly felled.

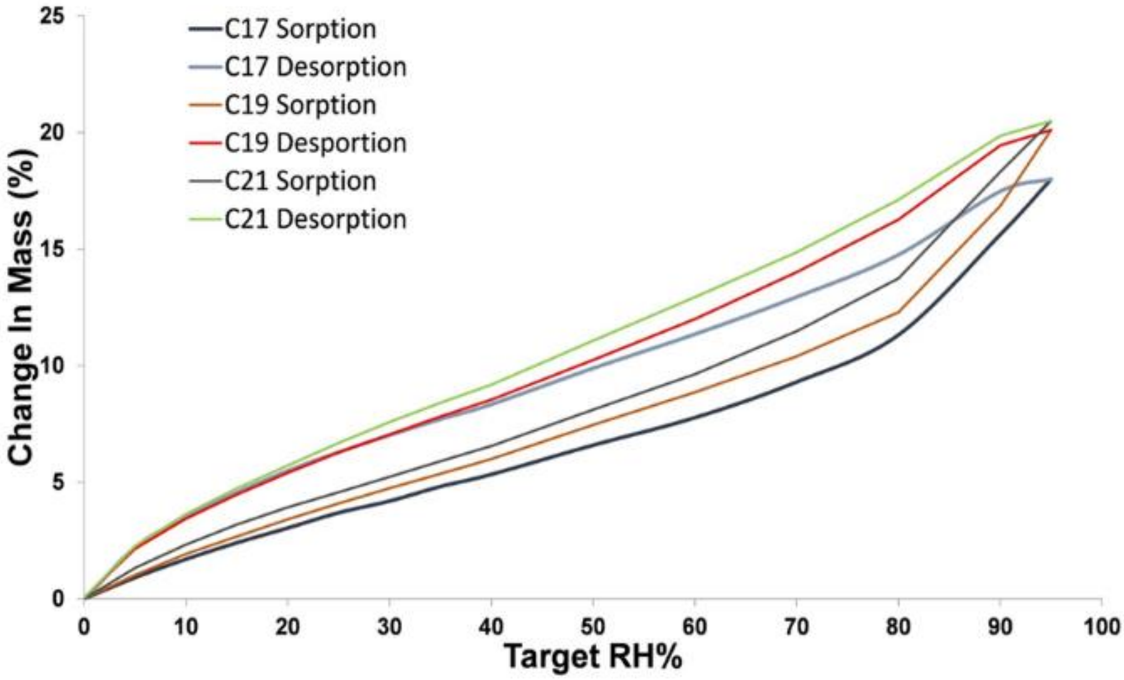

Figure 6. Sorption and desorption isotherms for three samples of oak felled in different centuries.

Climate Controlled Test Chambers

The experimental testing took place at the University of Bath's Building Research Park using their Large Environmental Chambers supplied by Temperature Applied Science (TAS) Ltd. The technical specification for the chambers is shown in Table 2.

Table 2. Technical Specification of TAS Climate Controlled Chambers at the University of Bath's Building Research Park:

Chamber	**Temperature (°C)**		**Relative Humidity (%)**		**Rainfall (L/min)**	**IR radiation (W/m^2 @ 1m)**
	Min	Max	Min	Max		
Indoor	+5	+40	10	95	N/A	N/A
Outdoor	-20	+40	10	95	0.1	1,200

The three panels, each measuring 1120 by 1120 mm, were mounted as part of a dividing wall between the two climate-controlled chambers (Figure 7 & Figure 8).

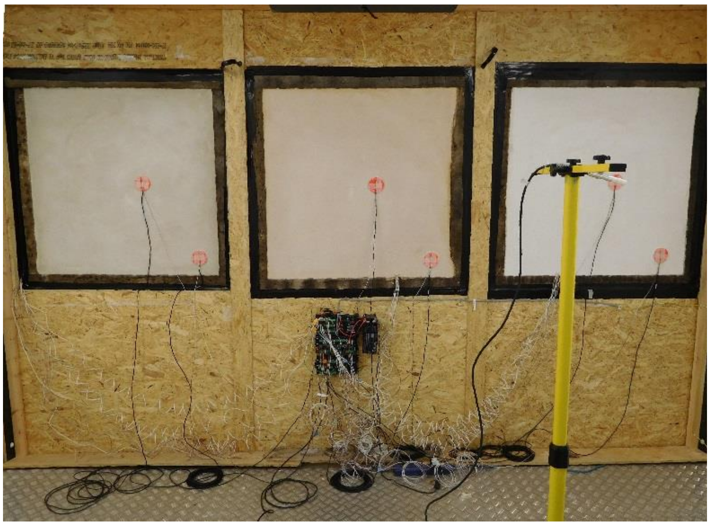

Figure 7. Panels in climate chamber. View from “internal” chamber.

Figure 8. Dual climate chamber

Monitoring positions and sensors

Temperature (°C) and moisture content (%) were monitored in four positions within each panel, one in the centre of the panel at a depth of 50mm and three at the midpoint of the lower timber frame, 800mm above floor level, at a depth of 10mm, 50mm and 90mm (Figure 3). The temperature was measured using type-T thermocouples (range -75°C to +250°C, accuracy ±0.5°C) connected to a Campbell Scientific® CR1000 data logger. The moisture content was measured using electrical resistance. For each monitoring position, copper wires were attached to two stainless steel screws, inserted in the oak frame, placed 20mm apart, parallel to the wood grain. The copper wires were connected back to a Campbell Scientific® CR1000 data logger measuring resistance, wired and programmed according to advice provided by Historic England (McCaig 2016), originally developed by Dr Paul Baker of Glasgow Caledonian University. This method was selected due to the potential for continuous measurements and the small size of the wire/screw arrangement, thereby limiting the influence of the sensor on the wall's performance. The wiring for both electrical resistance and temperature measurements was also routed to minimise the creation of any direct paths for hygrothermal movement.

In addition, the dry-bulb air temperature (°C) and relative humidity (%) of each climate chamber were monitored with Campbell Scientific® CS215 RHT probes (range- 0 to 100% RH, -40°C to +70°C, accuracy ±2% RH, ±0.4°C) at 1500mm above floor level. Concurrently, in situ U-value measurements were undertaken in accordance with BS ISO 9869-1 (British Standards Institution 2014). These measurements were taken in two monitoring positions per panel, one close to the centre (offset from the interstitial monitoring position to avoid interference) and 100mm from a corner to assess the edge effect from the timber frame. Measurements were made using Hukseflux HFP01 heat flux plates and type-T thermocouples connected to a Campbell Scientific® CR1000 data logger with readings taken at 5-minute intervals.

Steady State Measurements

For the initial three weeks of monitoring the test panels were subjected to steady state conditions with the aim of forcing increased moisture content. To determine the set temperature and relative humidity of the test chamber, Glaser calculations were undertaken in accordance with BS EN ISO 13788:2012 (British Standards Institution 2012). These calculations plot the vapour pressure against the saturation vapour pressure, across the thickness of the panel build-up under steady-state conditions and constant heat transfer. Where the vapour pressure touches the saturation vapour pressure, interstitial condensation is deemed to occur. The results of these calculations (Figure 9) showed that with internal conditions of 21°C/70% RH and external of

5°C/80% RH, interstitial condensation would occur within the wood fibre panel, and the wattle-and-daub would see an increase in moisture towards its inner face.

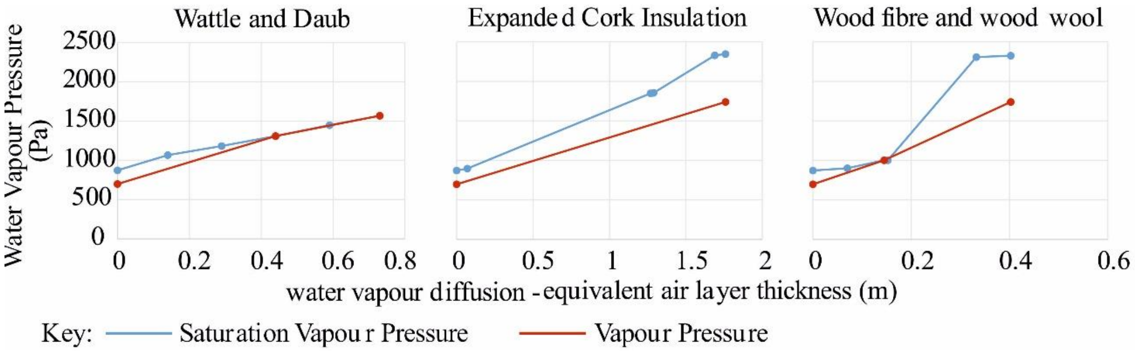

Figure 9. Glazer calculations according to BS EN ISO 13788:2012 for three infill panel constructions with external (left) conditions of 5°C and 80% RH and internal (right) conditions of 21°C and 70% RH. Source: (Author's own, 2017)

Conditions would have to be increased to 90% RH, internally and externally, to produce any increase in moisture content within the cork panel. Although subsequently modified, at the time of testing, prolonged operation of the climate chamber at 90% RH was not possible due to technical constraints. Therefore, the set points of 21°C/70% RH for the internal chamber and 5°C/80% RH for the external chamber were used for the initial three-week monitoring period.

Cyclical dynamic Measurements

Following the initial three weeks of monitoring under the steady-state conditions previously described, a further two weeks were then monitored using the same set points for the internal chamber but with diurnal cyclical climate for the external chamber, thereby recreating conditions closer to those found in reality. The definition of this climate was based on an average April day in the West Midlands (Met Office 2016). April was chosen due to the highest diurnal oscillation occurring in this month for this climate, and the West Midlands due to the location of the majority of case studies in the associated research project (Whitman 2017). As such the climate ranged from 5°C/94% RH to 12°C/61% RH and back over a twenty-four-hour period (Figure 10).

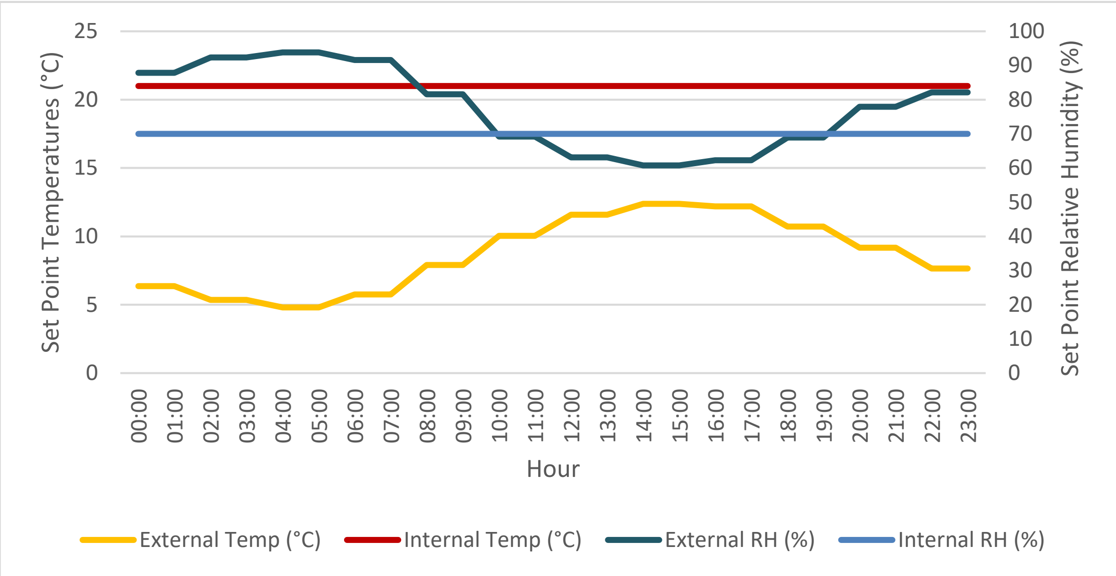

Figure 10. Set points for cyclical conditions for internal and external climate-controlled chambers. twenty-four-hour pattern repeated 14 times over two week period.

The overall total of 5 weeks monitoring was limited by the cost of running the chambers. Ongoing research is now being funded by Historic England that will allow for monitoring over an extended period (minimum 2 years).

Digital Hygrothermal Simulation

Following each of the monitoring periods the datasets were downloaded and analysed. The measured hygrothermal conditions within the two climate chambers were then used to simulate the interstitial hygrothermal performance of the panels using WUFI® Pro 5.3 (one dimensional hygrothermal movement) and WUFI® 2D (two dimensional). All material data used in the simulations was taken from the Fraunhofer materials database provided with the software. There is therefore a degree of error with the use of this material data, as it is data measured using German materials which may differ from the UK materials used in the construction of the test panels. This constraint is however unavoidable and common to all UK users, due to the lack of adequate data for UK building materials, especially those found in historic buildings.

Results

Thermal Performance

Table 3. Measured and calculated U-values

Panel type	Centre (W/m^2K)	Corner (W/m^2K)	Calculated (W/m^2K)
Wattle-and-daub	2.72	2.10	2.85
Cork	0.49	0.47	0.45
Wood fibre	0.59	0.60	0.63

The results of the in-situ U-value monitoring are presented in Table 3. Measured and calculated U-values along with the values calculated according to BS EN ISO 6946:2007 (British Standards Institution 2007). A positive edge effect is seen for the wattle-and-daub due to the thermal conductivity of the oak frame being lower than the panel. A minimal negative edge effect is seen for the wood fibre as the infill has a lower thermal conductivity than the frame. The minimal positive edge effect for the cork was not expected, however thermography showed this was due to a horizontal central joint in the cork panel reducing the thermal performance at the central measuring location. It should be noted that for both the cork and woodfibre, the difference between the centre and corner values is so minimal that it potentially may be due to measurement error factors rather than an edge effect. Overall the cork had the best thermal performance, with an average U-value of 0.48 W/m^{2}K.

Interstitial Moisture Content

Steady State Conditions

The moisture content measured in each panel during the steady state conditions are presented in Figures 11, 12 & 13.

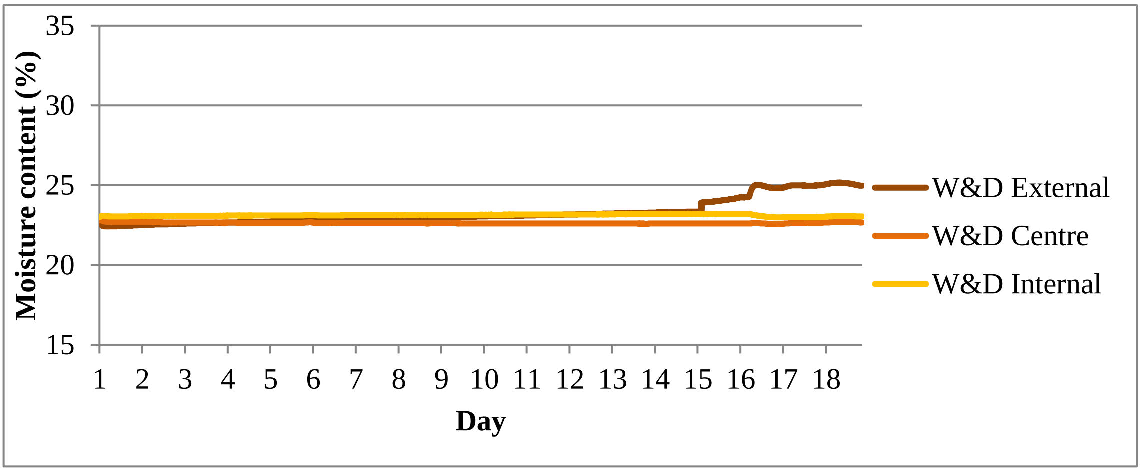

Figure 11. Interstitial moisture content (%) measured in Wattle & Daub (W&D) panel from 14/09/2017 to 02/10/2017 under steady state conditions.

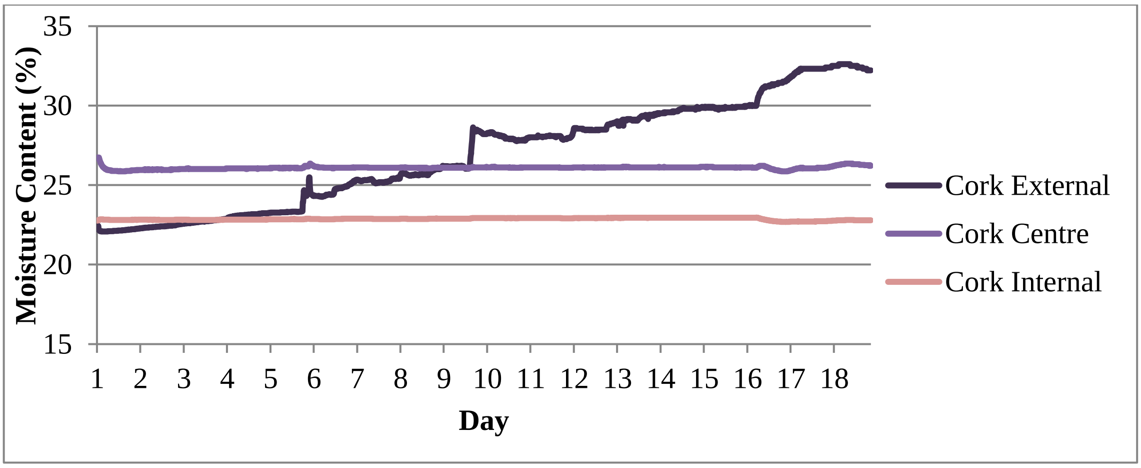

Figure 12. Interstitial moisture content (%) measured in expanded Cork panel from 14/09/2017 to 02/10/2017 under steady state conditions.

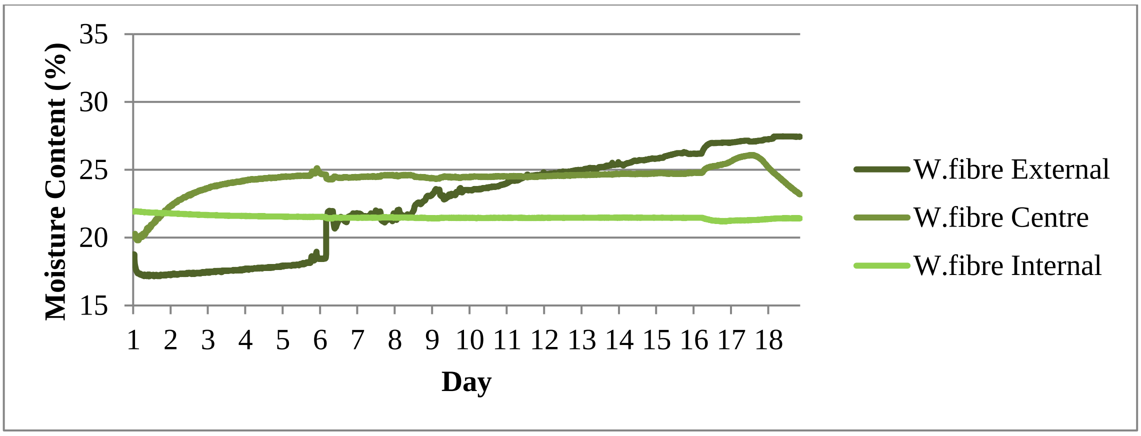

Figure 13. Interstitial moisture content (%) measured in Woodfibre and Woodwool panel from 14/09/2017 to 02/10/2017 under steady state conditions.

The panel with the most stable moisture content was the wattle & daub (Figure 11), with only a slight increase towards the external edge of the timber frame. This increase was also seen to a far great extent in the other two panels. The only other monitoring position to show an increase was the central location in the woodfibre and woodwool composite panel (Figure 13), confirming the predicted interstitial condensation.

These results were then compared with the Glaser calculations, the WUFI® Pro 5.3 and WUFI® 2D simulations and are presented in Table 4 which indicates if the moisture content increased, decreased or remained steady throughout the duration of the test/simulation period for each of the prediction methods, compared to the measured results. The final column of the table indicates if there was found to be agreement between the simulated and measured results for each monitoring location.

Table 4. Moisture content as measured and simulated for steady state conditions. Increase (↑), slight increase (↗), decrease (↓), slight decrease (↘) and steady (→). No agreement (×), agreement (✓), approximate agreement (≈). Key findings highlighted in red.

Infill	Loc.	Glaser	WUFI® Pro5.3	WUFI® 2D 3.3	Measured	Agreement
Wattle and Daub	Ext.	→	↓	↓	↑	×
	Cen.	→	↗	↗	→	≈

	Int.	↑	↑	↑	↗	✓
Cork	Ext.	→	↗	↓	↑	✘
	Cen.	→	→	→	→	✓
	Int.	→	↘	↑	→	✘
Wood fibre	Ext.	→	↗	↓	↑	✘
	Cen.	↑	↑	↑	↑	✓
	Int.	→	↓	↑	↓	✘

The results demonstrate that there was agreement between simulations and measurements for four of the nine monitoring positions (44%). Most importantly, the measured rise in moisture content in the centre of the wood fibre panel, arising from interstitial condensation, was successfully identified by all three prediction techniques. However, these failed to foresee the measured rise in moisture content in each of the three external lime renders. Equally there can be seen to be contradictions between results generated by the two versions of WUFI®. Further research is required to investigate any reasons for these discrepancies.

None of the simulation techniques nor the measured data showed any suggestion of interstitial condensation within the cork infill panel. Coupled with the superior thermal performance of this detail, these results would suggest that this potentially could be a good retrofit solution, assuming the three-dimensional characteristics of the frame were suitably plumb to accept rigid panels.

Dynamic Cyclical Conditions

The moisture content measurements in each panel during the period of dynamic monitoring are presented in Figures 14, 15 & 16.

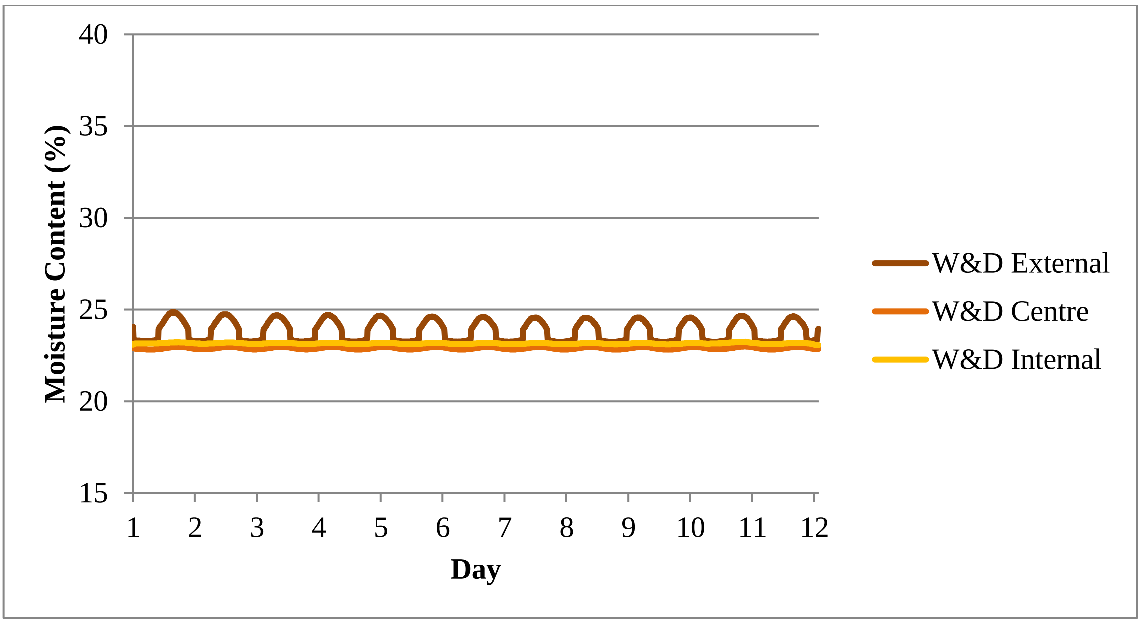

Figure 14. Interstitial moisture content (%) measured in Wattle & Daub (W&D) panel from 02/10/2017 to 13/10/2017 under dynamic conditions.

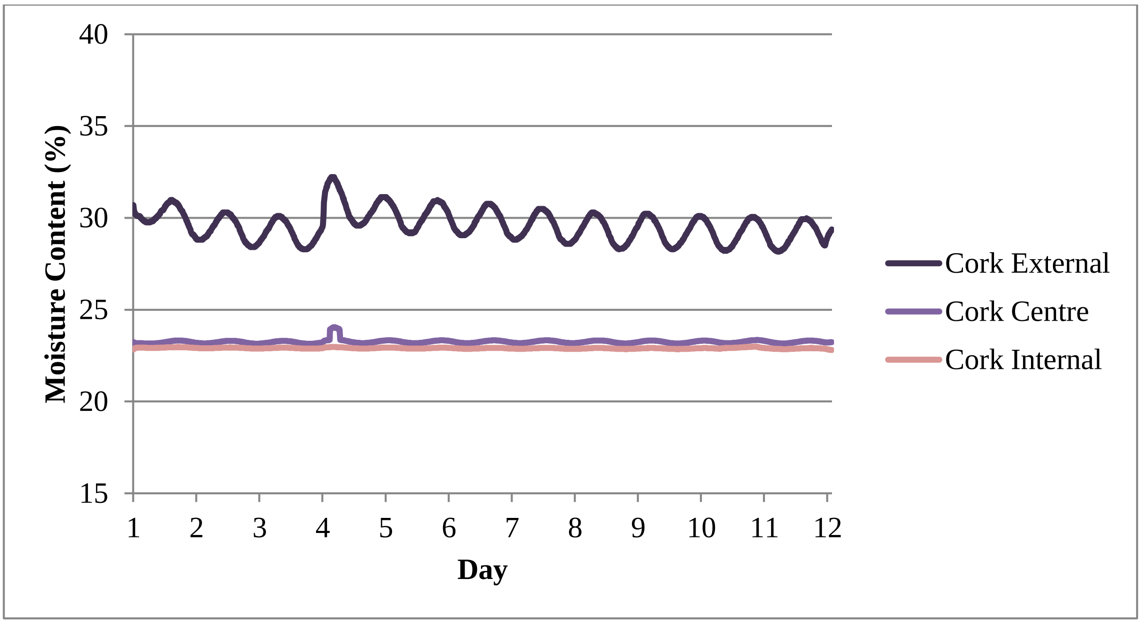

Figure 15. Interstitial moisture content (%) measured in Cork panel from 02/10/2017 to 13/10/2017 under dynamic conditions.

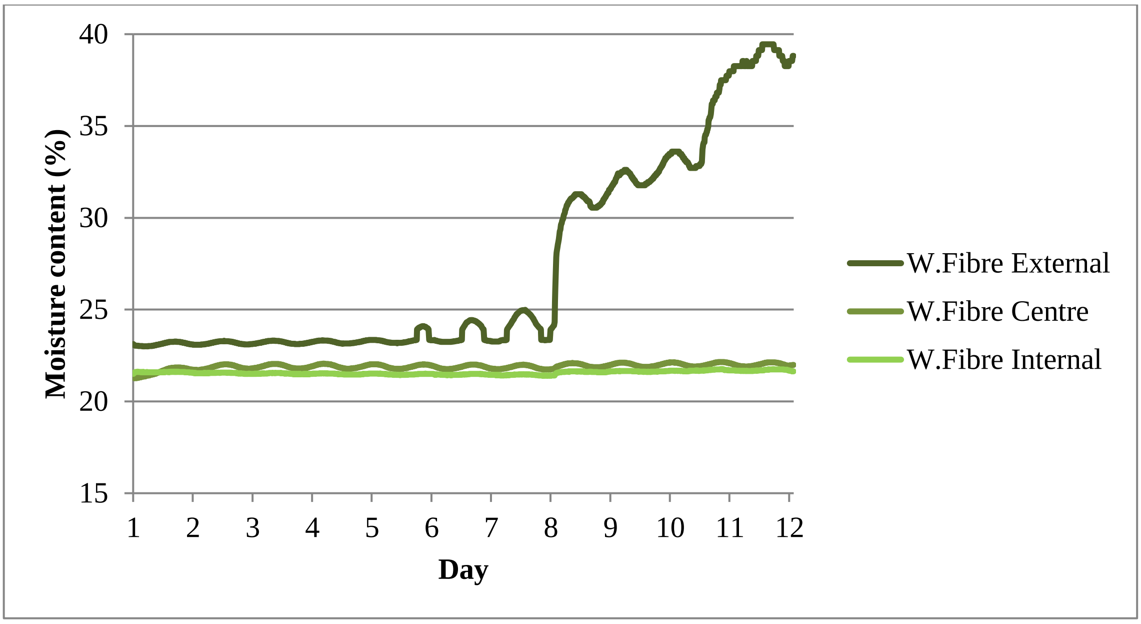

Figure 16. Interstitial moisture content (%) measured in Woodfibre and Woodwool panel from 02/10/2017 to 13/10/2017 under dynamic conditions.

Most of the monitoring positions show stable conditions, with only minor diurnal fluctuations, most noticeable in the external location. However, in the case of the monitoring position towards the external edge of the woodfibre panel, there was recorded a sharp increase, starting approximately halfway through the monitoring period.

As before, the results of the Glaser calculations, WUFI® Pro5.3 and WUFI® 2D 3.3 were compared with the measured results. These are presented in Table 5. It should be noted that the Glaser calculations do not make allowance for moisture storage or transfer, and as such it is not possible to perform dynamic calculations. However, Glaser calculations for each of the set point conditions (Figure 10) did show a condensation risk towards the interior face of the wattle and daub, and at the centre of the wood fibre for 50% of the time.

Table 5. Moisture content as measured and simulated for dynamic cyclical conditions. Increase (↑), slight increase (↗), decrease (↓), slight decrease (↘) and steady (→). No agreement (✗), agreement (✓), approximate agreement (≈).

Infill	Loc.	Glaser	WUFI® Pro5.3	WUFI® 2D 3.3	Measured	Total Agreement	Agreement WUFI® Pro5.3 & Measured
Wattle and Daub	Ext.	→	→	↘	→	≈	✓
	Cen.	→	↗	→	→	≈	✓
	Int.	↑	→	↗	→	✗	✓
Cork	Ext.	→	→	→	↘	≈	≈
	Cen.	→	↘	→	→	≈	≈
	Int.	→	→	↗	→	≈	✓
Wood fibre	Ext.	→	↑	→	↑	✗	✓
	Cen.	↑	→	↑	→	✗	✓
	Int.	→	→	→	→	✓	✓

From the results,again there are discrepancies between simulated and measured results and between different simulation methods. However, there is a good agreement between the WUFI® Pro5.3 and the measured results, with the only locations in disagreement being the centre and external edge of the cork panel. This disagreement may be explained by the initial moisture content of the lime based adhesive layer between the two layers of cork boards being set too high in the simulation. WUFI® Pro5.3 also successfully identified the increase in moisture content for the external edge of the woodfibre panel. As such it would appear from these results that this simulation programme provides more consistent results than Glaser calculations or WUFI® 2D 3.3.

Overall, from the measured results only an increase in moisture content was measured towards the external face of the wood fibre panels. This in conjunction with the risk of interstitial condensation under forced steady state conditions, raises concern over this replacement infill detail. It should however be noted that this was only over a two-week period under a single diurnal climate variation and further research is required over a longer timescale under more realistic climatic conditions.

Conclusions

The results show that for steady state conditions the simulations successfully anticipated interstitial condensation where it occurred, however increases in moisture content towards the external face of all three panels were not predicted.

For the dynamic cyclical conditions the simulated results from WUFI®Pro 5.3 closely matched those measured in reality, however there were discrepancies with both Glaser calculations and WUFI® 2D 3.3.

Overall the cork infill detail performed the best, with the greatest thermal performance and no interstitial condensation being identified. It should however be noted that these results are for forced steady-state conditions that are unlikely to exist in real life or for more realistic conditions over only a two-week period. Further research is therefore required before the practical implications of this study can be fully verified. Work has now started on a subsequent research project funded by Historic England that will allow longer term monitoring of test panels exposed to real external climatic conditions. The construction of this project is underway with initial results anticipated in 2021.

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