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Heritage retrofit and cultural empathy; a discussion of challenges regarding the energy performance of historic UK timber-framed dwellings

Structured Abstract

<p><i>Purpose of this paper</i></p>	<p>The energy retrofit of the existing building stock, and specifically the thermal upgrading of the buildings' envelopes, has been identified as a key action for both the decarbonisation of the built environment and the reduction in fuel poverty. When considering the energy retrofit of heritage buildings it is however important to recognise both the technical issues that this entails and the potential impact on their cultural value and the emotional responses to it. This paper focuses on the thermal upgrading of historic timber-framed buildings in the UK.</p>
<p><i>Design/methodology/ approach</i></p>	<p>The paper begins by exploring the cultural significance of this form of building construction, before examining three case studies using both quantitative and qualitative methodologies.</p>
<p><i>Findings</i></p>	<p>The results show that whilst the application of energy retrofit actions to this emblematic typology may have limited success, the emotional connection of the buildings' occupants often results in the work resulting in higher user satisfaction than would otherwise be expected.</p>
<p><i>Research limitations/implications</i></p>	<p>Although limited in number, the three case studies provide an insight into the complex issues surrounding the low energy retrofit of historic timber-framed buildings. Further research into this area is encouraged.</p>

<i>Practical implications</i>	The paper contains the monitoring of specific retrofit details, the results of which should inform future projects.
<i>Social Implications</i>	The review of the cultural significance of historic timber-frame buildings in the UK underlines the importance of the conservation and continuing survival of these buildings.
<i>What is original/value of paper</i>	Previous heritage retrofit research in the UK has focused on solid wall construction with little investigation into the issues surrounding the retrofit of historic timber-frame buildings. This paper explores this previously under-researched area. Additionally, this paper begins to explore the possible links between occupants' emotional connection to historic buildings and their perceived levels of comfort.

Introduction

In 2018, the Intergovernmental Panel on Climate Change (IPCC) reiterated that reductions in heating and cooling demand, and specifically building envelope improvements, present the largest energy saving potential in the built environment (IPCC, 2018 p.141). The same report acknowledged that in developed countries, this would primarily be in the form of energy retrofits of the existing building stock (ibid, p.142). In 2014 the UK government committed to improving the energy efficiency of our current building stock in order to achieve carbon emission targets (DECC, 2014 p.73). They too identified energy efficient renovation as the overarching approach for realising this, with the thermal improvement of the buildings' envelopes as their first principle (ibid.). However, when considering historic buildings it is important that these thermal improvements have limited negative impact on both their heritage value and their historic built fabric. As such it is important to

understand both the cultural significance of these buildings and the technical conflicts that may arise (Historic England, 2012).

It has been estimated that approximately 22% of dwellings in England and Wales were built pre-1919 (Nicol et al., 2014 p.4-5), as were 45% of non-domestic properties (Pout et al., 1998 p.10). Of these approximately 1.2% of pre-1919 dwellings and 2% of pre-1919 non-domestic properties are of traditional timber-framed construction (Whitman, 2017).

Although small in number, totalling around 68,000 (ibid.), these buildings with their loadbearing timber structure, often exposed both internally and externally, hold a special place in the national, and especially English, notion of cultural identity. It has been asserted that there is something quintessentially English about these buildings (Ballantyne and Law, 2011b p.125), something that elevates their place in the national conscience. This paper aims to explore the communal or associative values of historic timber-framed buildings in the UK, before examining how these values impact on the energy retrofit of these buildings, through the analysis of three case studies.

Whilst it has been acknowledged that those who live in naturally ventilated buildings usually accept a wider range of comfort temperatures (Givoni, 1994 p.39) and psychological adaptation is identified as an influencing factor in adaptive thermal comfort (Humphreys, 2015 p.100), little research has been undertaken into the correlation between occupants' perception of their home's cultural value and their perceived comfort. In general it has been noted that few studies exist that examine the role of the occupant in the assessment of historic building retrofits (Fouseki and Cassar, 2014 p.97), with those that do, focusing either on the occupants' decision making process (Sunikka-Blank and Galvin, 2016) or the effect of their behaviour on energy use (Ben and Steemers, 2014). This paper begins to explore the links between occupants' associative and heritage values and their perceived thermal comfort.

The cultural significance of historic timber-framed buildings in the UK

The publication of the Burra Charter (ICOMOS, 2013) was possibly one of the first times that the concept of cultural significance was clearly articulated, especially when related to the management of the historic environment (Worthing and Bond, 2008). The charter defines cultural significance as the “aesthetic, historic, scientific, social or spiritual value for past, present or future generations” (ibid, p.2). These values have now been adopted by most heritage bodies both internationally and in the UK (Historic England, 2008 p.27, Cadw, 2011 p.16, Historic Environment Scotland, 2016 p.48) and inform planning policy (Ministry of Housing, 2019). In England and Wales these values are expressed as Evidential Value - the fabric of the asset itself; Historic Value - events, people or lifestyles represented or associated to the asset; Aesthetic Value - the sensory or intellectual pleasure that the asset evokes; and Communal Value- the meaning the asset has for those who relate to it (Ibid.). Whereas in Scotland the terms used are Intrinsic, Contextual and Associative values (Ibid.). The first part of this paper aims to explore the communal and associative values of historic timber-framed construction in the UK. It begins with a summary of its ongoing influence, even once it ceased to be a common construction technique, before turning to examine the reasons behind its enduring popularity.

The Endurance of a Style.

Timber construction in the UK can be traced back to Neolithic times (Hillam et al., 1990 p.214) however fully timber-framed buildings, as commonly understood in the UK today, appear to have developed around the late 12th century (Walker, 1999 p.21). Surviving examples of such buildings can be found at Fyfield Hall, Essex (Bettley and Pevsner, 2007 p.375) and the Wheat and Barley Barns at Cressing Temple, also in Essex (ibid. p.313). From this time until the 1600s, timber-framing became a common construction technique (Harris, 2010) but fell out of favour in the late 17th century, following the Great Fire of London (Reddaway, 1940) and similar conflagrations in cities across the country (Borsay,

1989). However, even after timber framing ceased to be a standard structural solution, its aesthetics continued to be replicated, from the eighteenth century *cottage orné*, to the Victorian *Olde English Style* and the *mock-Tudor* houses of inter-war suburbia. The enduring influence of timber-framed buildings can be seen to this day, be it implicit, as seen in the applied timber screens or tile hanging of the RIBA House of the Year award winners 2016-2018 (RIBA, 2018) or explicitly reproduced on mass housing.

Age Old Roots, Rural Idylls and the Handmade

It has been attested that our fascination with the timber-frame results from its links to the past, and more specifically a Tudor past (Ballantyne and Law, 2011a, Ballantyne and Law, 2011b, Stamp, 2006, Simpson, 1977). There is clear evidence for their reasoning. The “Tudor” period, from the crowning of Henry VII in 1485, until the death of Elizabeth I in 1603, is revered as a golden age of England (Ballantyne and Law, 2011a p.16). Its monarchs are seen as the most English of monarchs (ibid. p.30), which coupled with Henry VIII’s break from Rome, and the links with Shakespeare all add to the celebration of this age as truly “Old England” (Stamp, 2006 p.5).

Yet if the imitation of the style was specifically to create an association with the Tudor age, would it not be more precise to use architectural styles developed under Tudor rule? If so, then surely the emerging renaissance architecture of Elizabethan houses such as Hardwick Hall or the great brick palaces of Henry VIII would be better archetypes to follow. Similarly, it is not the most emblematic Tudor timber-framed buildings that are reproduced, for example those in the ornamental style epitomised by houses such as Little Morton Hall. Instead, they look towards the vernacular architecture of the Kent and Sussex Weald, as so clearly illustrated by the work of architect George Devey, 1820-1886 (Allibone, 1991) whose work was to influence Richard Norman Shaw and William Eden Nesfield (Ibid. p.29, 44 & 81). Could it not therefore be said that these buildings did not look back to a specific Tudor past, but rather to a more generic Old England? A simpler, pre-industrial “time-gone-

by”? (Simpson, 1977 p.36, Ballantyne and Law, 2011a p.38-39). Girouard narrated that “Dislike of the present led them to the past, dislike of the town, the country...” (Girouard, 1977 p.5).

The rural idyll and the picturesque

Timber framing is essentially seen as a rural architecture, as such, just as it represents the past, it is also synonymous with the countryside. The romantic movement of the 18th and 19th century moralised the dichotomy between town and country, with health, honesty and virtue being characteristics of the country and corruption, greed and vainglory the town (Tuan, 1974 p.236). In the 1870s, as Britain was losing its industrial supremacy to Germany and the United States (Howkins, 1986 p.63), the metaphor of “*the workshop of the world*” (MacLeod, 2014) fell out of favour, with industrialization increasingly seen as something un-English (Daniels, 1991 p.15). As pride in the industrial north faded and power moved south (Howkins, 1986 p.65), the “*workshop of the world*” became replaced with a “*green and pleasant land*” (Bunce, 1994 p.21) and more specifically one formed by an idealised “*South Country*” (Howkins, 1986 p.65), a notional definition of rurality, embodied in the countryside of southern England as seen by those looking out from the urban world (ibid p.64).

At the same time, traditional rural life was under threat, whereas once industry had attracted people to the city, the lack of rural employment of the late 19th century now drove them to it (Lowe, 1989 p.12). As the productivity of the countryside declined, its potential as an escape from the city increased, both physically through the emergent rail network (Howitt, 1844 p.316-5) and ideologically such as through Cadbury’s Chocolate boxes’ illustration with rural scenes painted by artists such as Myles Birkett-Foster (Short, 2006 p.141). Just as the works of Birkett-Foster, Wordsworth, Constable, Turner, et al provided a link for the city dwellers to the rural idyll, so did timber framing become the shorthand for the vernacular architecture of the “*South Country*” (Jackson, 1973 p.140).

Therefore, we can see that the significance of timber-framed architecture can be traced to the past, be it a specific Tudor past or a more generic past. At the same time, it draws on a desire for an escape from the city, a return to the country. However, if these were the only issues at play here, could you not say the same about stone cottages or other rural typologies?

The materials of timber-framed buildings, the oak for the frame, the hazel withies for the wattle and the earth for the daub, come directly from the land, thereby making it truly an architecture with roots. On the frontispiece of Laugier's 1753 *Essai sur l'architecture* (Laugier, 1977) his "*rustic hut*" is shown constructed of tree trunks growing from the ground, underlining timber-framed buildings' "*fundamental link between soil and house, nation and village, as if the cottage had grown up out of the land on which it stood*" (Sayer, 2000 p.115) a sentiment shared by the interwar Conservative Prime Minister Stanley Baldwin, in his inaugural speech to the Royal Society of Arts, January 26th 1927 (Daily Mail, 1927 p.59). Baldwin also highlighted it as a link to the mediaeval craftsman (ibid). Though his assertion may be questioned since the craftsmanship in machine cut applied timbers of contemporary designs was limited, we find here another component of the significance of timber framing, that of the handmade. There is the sense that almost anyone could, if not build from scratch, at least add to and amend a timber-framed, or apparently timber-framed home (Ballantyne and Law, 2011a p.125, Ballantyne and Law, 2011b p.140). Equally there is the acknowledgement of the skill and care of the artisan. This embodiment of the craftsman skill and ancestral knowledge are recognised internationally by ICOMOS as the key values of wooden architecture (ICOMOS, 2017).

In a world in which production becomes increasingly mechanised there is a counter-reaction to perfection, an attribute previously aimed for by the skilled artisan, and the irregularities resulting from manual labour become more highly prized (Osborne, 1977,

Sennett, 2008 p.84). A key factor in the added value of “the handmade” has been identified as the perceived love and personal care invested in the production of the product by the craftsman, as opposed to the impersonal, emotionless work of the machine (Fuchs et al., 2015). Timber framing with its axe signatures, saw marks and carpenter’s marks, clearly manifests the hand of the artisan in its production, and as a consequence, Fuchs et al would argue, their love.

The enduring importance of timber-framed buildings in the British or more specifically English cultural identity would therefore appear to be a combined result of three key factors. A connection to the past, be this specifically a Tudor past or a more general times gone by; its evocation of the rural idyll, being not only present in the countryside but physically made of it; and the evidence of the hand of the craftsman, increasingly valued in an progressively mechanised world. All three are symptoms of the industrialised world, the desire to return to a time before it, to escape from the city created by it and a rejection of the perfection it has enabled. We have seen that even after timber framing ceased to be a common structural solution, its aesthetics continued to be replicated. Yet these imitations underline the need to conserve the remaining examples of true timber-framed buildings that inspired them. If we were to be left with only reproductions, with their half-timbers only skin deep, then an integral part of our identity would be lost. It can be argued therefore that the continued use of historic timber-framed buildings and their conservation is of national importance. The following case studies look at the low energy retrofit of three historic timber-framed dwellings, examining their success both quantitatively and qualitatively.

Case studies

With many low carbon retrofits, the main objective is the reduction of greenhouse gas emissions. However, given the small percentage of the total domestic building stock

represented by historic timber-framed dwellings, reducing their emissions will have a minimal impact. The overriding aim of retrofitting these properties should therefore be to ensure that these buildings provide reasonable comfort to their inhabitants and by doing so enabling their continued occupation and survival. As such, there is a focus on the thermal performance of the building's envelope. At the same time, it is essential that any retrofit actions do not put at risk the historic building fabric nor damage the previously identified buildings' heritage value.

The three buildings chosen are, a mediaeval peasant hall now let as holiday accommodation; an estate cottage built over three centuries, now let by the National Trust as a single-family residence; and a farm house dating from the 16th Century in private ownership. As such, the case studies represent a variety of ownership models, tenancies and uses. The first and third case studies have undergone substantial retrofits and display a variety of different panel infills, both old and new. In the case of the first, this work was designed and overseen by a local, sole practitioner architect. In contrast, the second case study has had minor retrofit interventions with no change to the existing panel infills, with the works specified by the Estate surveyor in line with the National Trust's environmental standards. The retrofit of the third case study dates from prior to the current ownership and appears to have been undertaken without planning permission or listing building consent. Proposals to rectify the damage caused by this retrofit have recently been granted planning permission.

Location

The first two case studies (1 & 2) are both located in the county of Herefordshire, in the English West Midlands or Welsh Marches. Figure 1 illustrates that this county encompasses the southwest quadrant of a western concentration of timber-framed buildings in the UK. The predominant panel infill materials in Herefordshire are exposed brick (47%), lime plaster or cement render (44%) and wattle and daub (8%) (Whitman, 2017 p.218). A high

proportion of buildings with modern infill can also be found locally, with 16% of those listed with twentieth century infills located within the county boundaries (ibid).

The third case study is located in Suffolk, in East Anglia, an area encompassing the highest concentration of historic timber-framed buildings in the UK (44%) (ibid, p.153). The predominant panel infill materials in Suffolk are lime plaster or cement render (53%), followed by completely rendered buildings (34%) and timber clad buildings (8%). The remaining 5% are divided between brick, wattle and daub, tile-hanging, stone and modern infill.

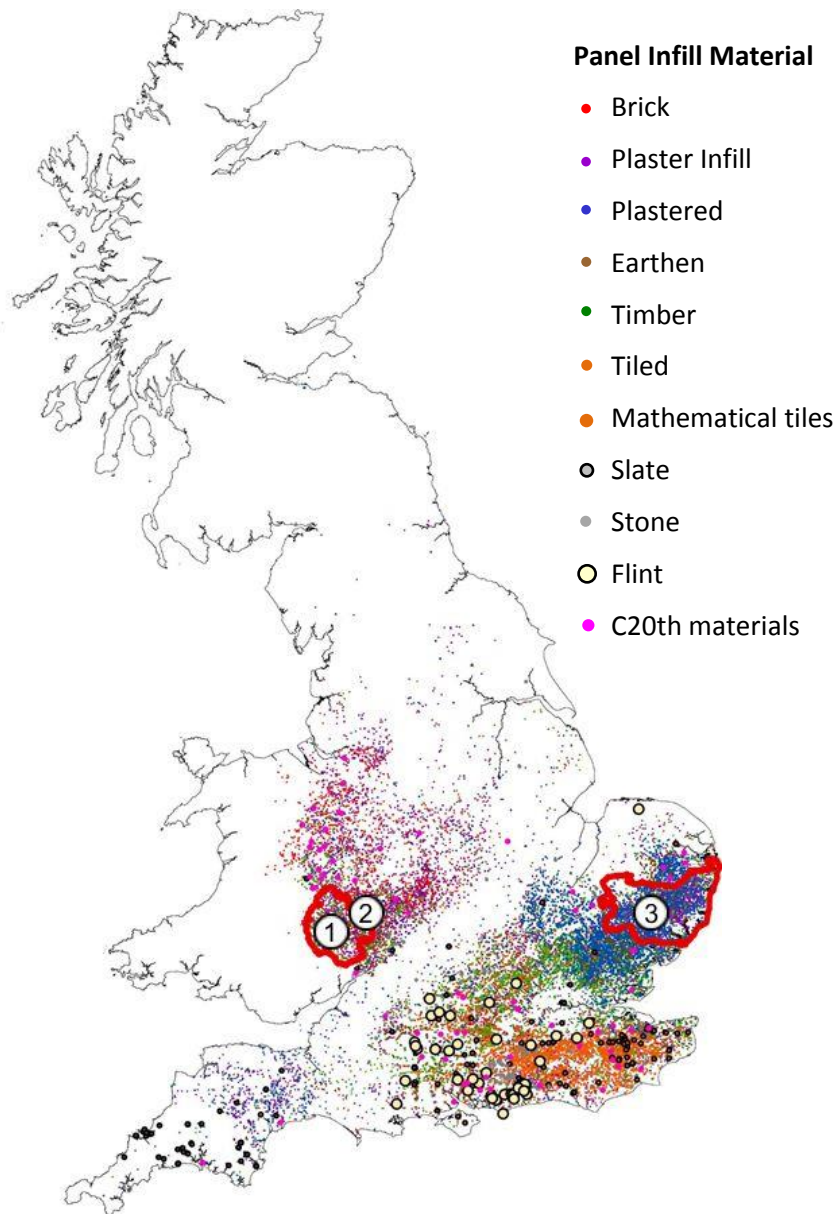


Figure 1. Distribution of timber-framed buildings in Great Britain by infill material, showing location of case studies and associated counties. Source: (Author's own based on data from (Historic England, 2014, RCAHMW, 2014))

Climatic Conditions

The majority of the UK is located in a temperate maritime climate with warm summers and cold winters, classified under the Köppen-Geiger climate classification system as Cfb (C-Warm temperate, f-fully humid, b-warm summers) (Kottek et al., 2006). The heating season typically lasts from November until March with no requirement for mechanical cooling during the summer months. Figure 2 shows the climates for Herefordshire and Suffolk

generated using the software Meteotest™ version 6.1, compared to UK average values as published by the Met Office (Met. Office, 2009).

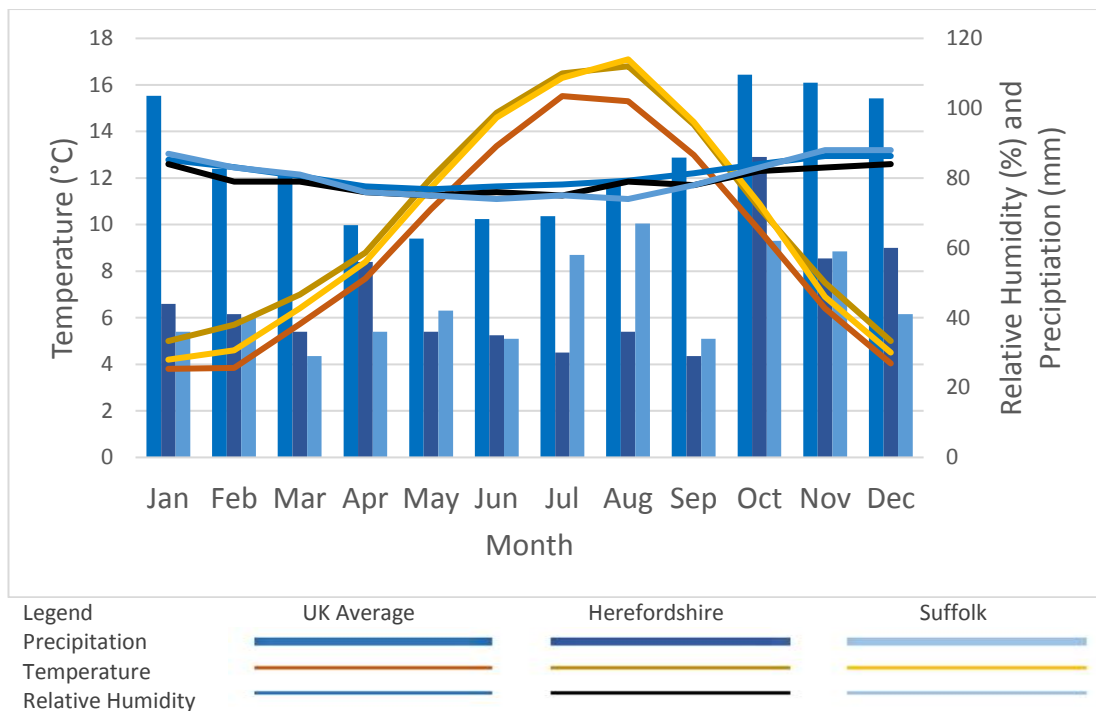


Figure 2 Climatic data for UK, Herefordshire and Suffolk. Source: (Meteotest, 2016, Met. Office, 2009)

Both counties share similar temperatures, higher than the UK average. Levels of relative humidity are consistent with the UK average but precipitation is lower. Suffolk receives marginally less (538mm) than Herefordshire (546mm) over the year, however, the pattern of precipitation differs considerably. Suffolk experiences the maximum levels of precipitation during the summer months, the inverse to the UK average, due to the summer thunderstorms that are more common in the east of the country (Manley, 1955 p.262). It should be noted that Herefordshire has a fairly dry climate considering its western location due to the rain shadow of the Welsh Mountains (Phillips, 2013 p.117).

Methodology

Quantitative monitoring

In situ hygrothermal monitoring was undertaken, including U-value measurements following BS ISO 9869-1:2014 (British Standards Institution, 2014), thermography following

best practice guidance (Hart, 1991, Young, 2015), pressure testing according to BS EN ISO 9972:2015 (British Standards Institution, 2015) and measurements of internal hygrothermal comfort based on criteria defined by Givoni (Givoni, 1998) using TinyTag Ultra 2 TGU-4500 sensors. The measured in-situ U-value measurements were then compared to U-values calculated according to BS EN ISO 6946:2007 (British Standards Institution, 2007) with values taken from BS EN 12524:2000 (British Standards Institution, 2000). Timber moisture content was also monitored but the detailed results are not presented in this paper. Due to personal circumstances of the tenant at case study 2, equipment could not be left onsite, thereby limiting monitoring to only thermography, pressure testing and timber moisture content at this case study. It was however possible to monitor this property both pre and post-retrofit.

Quantitative simulation

Simulations were undertaken using the software DesignBuilder Version 4.2.0.54, a graphical interface for the dynamic simulation engine EnergyPlus DLL v8.1.0.009 (Design Builder, 2014). For the building thermal zone calculation, EnergyPlus uses a heat balance model based on the assumption that the air in each building zone is homogenous with no stratification of temperature (Crawley et al., 2001 p.323). The complicated timber-frame was therefore simplified to block sub-surfaces, the area of which accurately represents the area of timber-frame, if not its precise location and configuration (Figure 3).



Figure 3. DesignBuilder models of (from left) case studies 1, 2 and 3. Source: (Author's own, 2017)

Simulations were undertaken for each of the retrofit solutions undertaken at the case studies, with each of the individual retrofit actions simulated separately in order to assess their specific impact on the buildings' heating energy demand. In addition, simulations of the combined effect of multiple retrofit actions, both real and hypothetical scenarios, were undertaken to compare the current and future potential performance of these buildings.

Qualitative monitoring

At case studies 2 and 3 a simple semi-structured interview was devised following the guidance given by Nichols et al (Nichol et al., 2012) using an adaption of the Bedford comfort scale from 1-very cold, to 7 very hot (Bedford, 1936) and including observations on the occupants current and typical behaviour with relation to their thermal comfort. Direct interviews were not possible at case study 1, however access to the visitors' book of this holiday accommodation allowed a systematic review of guests' comments.

Summary of case studies

Table 1 summarises the key statistics of the three case studies. It can be seen that case study 3 is the largest property, with case studies 1 and 2 being similar in size and case study 1 being the most compact property.

Table 1. Key statistics of three case studies

Parameter	Case Study 1	Case Study 2	Case Study 3
Age	C15 th	C16 th	C16 th
Tenancy	Holiday let	Let	Owner occupied
Net Floor area (m ²)	101	157	238.5
Area of External Envelope* (m ²)	425	430	734
Percentage of External Envelope (%)			
Surfaces in contact with the ground	14.6	23.1	19.3
Timber-framed wall	28.3	25.9	41.5
Masonry wall	33.8	15.6	0
Openings	1.9	3.3	5.4
Roof	21.4	32	34

* Including surfaces in contact with the ground

There follows more detailed descriptions of each case study and the associated results of in-situ monitoring, digital simulation and the occupants perceptions of comfort.

Case Study 1

Introduction

Case study 1 is a 15th century cruck hall in the Wye Valley, Herefordshire. For much of the 20th century it lay abandoned and derelict, before being restored 2000 – 2012. It now provides holiday accommodation. The renovation involved three different approaches to wall infill panels, retaining surviving oak lath and lime plaster panels where possible (7% of infill panels by area); new wattle-and-daub panels (18%); and multi-foil insulation (46%), the foil held by upright staves within a void, finished internally and externally with lime plaster on expanded metal lath. The distribution of these panels is shown in Figure 4.



Figure 4 Case study 1. Diagram showing location of each infill panel type. Source: (Author's own, 2016)

A new thatched roof was installed using reed from the Tay Estuary and Sedge, for the ridge, from the Norfolk Broads (Williams, 2011). From 2012 until 2015 the central bay of the hall was left with no internal finish to the underside of the thatch. Following pressure testing by the authors in 2015 it was decided to torch (lime-plaster) the underside of this central section. The ground floor slab is a new construction due to the need to relocate the building by approximately 500m during restoration. The slab construction is limecrete on expanded clay insulation, finished in sandstone flags.

In situ measurements

In situ monitoring was undertaken in 2015 (Whitman and Prizeman, 2016). A summary of the results are shown in Table 2.

Table 2. Results of in situ monitoring at case study 1, March & November 2015

U-value		
Material	Measured U-value (W/m²K)	Calculated U-value (W/m²K)
Repaired original lath and plaster	2.51	2.40
New Wattle and daub	3.25	2.99
Lime plastered Multi-foil insulation	0.71	0.41
UK building regulations Part L1B	-	0.70 [†]
Airtightness		
	Air changes per hour @50 Pa	Air permeability @50 Pa (m³/(h·m²))
Pre-torching of thatched ceiling	130	154
Post-torching of thatched ceiling	68	80
UK Building Regulations Part L1A	-	5*
Hygrothermal Comfort		
	Percentage of hours comfort achieved[‡] pre-torching (%)	Percentage of hours comfort achieved[‡] post-torching (%)
Exterior	8	5
Main Hall	53	70
Bedroom (ground floor)	17	25
Bathroom	67	85

[†] U-value for existing building with change of use. In this case from farm building back to house

* An air permeability index is stated only for new constructions

[‡] Percentage of occupied hours where hygrothermal conditions comply with criteria defined by Givoni (Givoni, 1998)

Those panels incorporating multi-foil insulation achieve the lowest u-value but do not achieve the anticipated calculated value, perhaps due to the internal staves and the exposed oak frame, both identified as thermal bridges by thermography. The pressure testing shows the airtightness of the house to be extremely poor, partly due to infiltrations between the infill materials and timber-frame, however, the untorched thatch roof was a major contributing factor. Following torching of this element the air permeability index is almost halved. The effect of this can be seen in the increase in the percentage of occupied hours where hygrothermal comfort is achieved, even despite the external climate being less favourable.

Energy Use Simulations

Four scenarios of infill panels were simulated using the measured U-values. The first imagined all lath and plaster panels had survived; the second imagined all panels had been replaced with new wattle and daub; the third that all had been replaced with the new multi-foil panels; and the fourth simulated the as-built situation with a mixture of all three

panel types. These four scenarios were simulated with both the pre- and post-torching air-change-rates and a third hypothetical air-change-rate of 10 ac/h@50Pa.

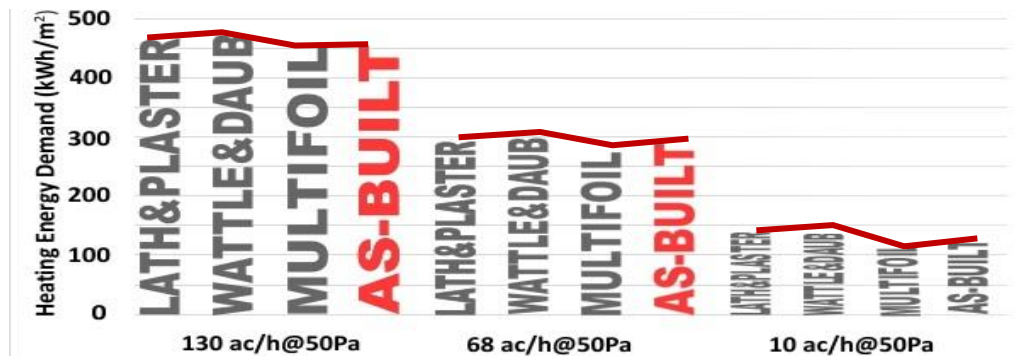


Figure 5. Simulated Heating Energy Demand (kWh/m²) for case study 1. Hypothetical scenarios in grey

Figure 5 illustrates the high heating demand of this case study, with a building energy index of 455 kWh/m², principally due to the poor airtightness of the building envelope. It can also be seen that the performance of the infill panels has little effect on the heating energy demand with a variation of only +4% and -0.01% when compared to the current situation. However, the simple act of torching the underside of the thatched roof, thereby improving the airtightness, sees a 36% reduction. Further work, such as improving the joints between panel and timber-frame and plugging post-holes could potentially improve the airtightness to a hypothetical 10ac/h@50Pa, thereby achieving a reduction of 72%. Whilst for this specific property no historic fabric was lost in the upgrading of the infill panels, the results of these simulations should have significant weighting in the planning of future retrofits of historic timber-framed buildings.

Occupants' perceptions of comfort

Of the 173 guests who had written in the book, between the house opening in August 2011 and July 2017, 12% commented on the house being cold and draughty, whilst 9% commented on it being warm or cosy. The other 79% entries in the guest book made no mention of thermal comfort conditions within the house, commenting instead on their delight of staying in a 14th Century cruck hall and the quality of the restoration work that

the owner and his architect had achieved. It is interesting to note that all of the comments related to the house being cold or draughty were written prior to the torching of the thatched ceiling, confirming the impact of this action.

Case Study 2

Introduction

The second case study, let by the National Trust as a private residence, is located on the Brockhampton Estate in North East Herefordshire and has sections dating from the 16th, 17th and 19th Centuries. In response to the Minimum Energy Efficiency Standards for let properties (MEES) (2015) the National Trust developed a set of environmental standards specifically for their let estate. These standards aim to achieve an Energy Performance Certificate (EPC) of E or above, with the minimum intervention. The complete refurbishment of this property, following the end of a long lease, enabled the implementation of these standards, resulting in the fitting of secondary glazing and installation of roof insulation. No interventions were made to the walls or solid concrete floor. Thermography indicated that most infills were of modern concrete block, although some surviving wattle and daub was positively identified.

In situ measurements

As previously noted, due to the personal circumstances of the occupant, no monitoring equipment could be left onsite, therefore measurements were limited to pressure testing and thermography which were undertaken in June 2015 prior to the retrofit and in November 2015 following its completion. The results are presented in Table 3.

Table 3 Results of in situ monitoring at case study 2, June & November 2015

Airtightness	Air changes per hour @50 Pa	Air permeability @50 Pa (m ³ /(h·m ²))
Pre-retrofit	16.5	17.8
Post-retrofit	10.8	11.7
UK Building Regulations Part L1A	-	5*

* An air permeability index is stated only for new constructions

The increase in airtightness resulting from the installation of the secondary glazing is noticeable. Whilst beneficial with regards to energy efficiency, there could be some issues concerning increased internal moisture levels. This was particularly noted in the bathroom where no controlled ventilation strategy had been implemented. Thermography showed an improvement of the thermal performance of the roof.

Energy Use Simulations

The two retrofit actions (secondary glazing and roof insulation) were simulated separately. In addition, two hypothetical retrofit actions were modelled, the first replacing all concrete block infill panels with woodfibre insulation and the second replacing all infill panels, including historic wattle and daub. Combinations of all retrofit actions, both real and hypothetical, were also simulated.

The results (Figure 6) demonstrate that the installation of secondary glazing is more effective (10% reduction) than replacing all the infill panels (9% reduction). Whilst it can be argued that secondary glazing is visually intrusive it is however a fully reversible retrofit action and does not result in the loss of historic fabric. The insulating of the roof is the retrofit action with the greatest individual benefit (25% reduction) which when combined with the secondary glazing results in an overall reduction of 34% and is the solution that was applied in reality with a building performance index of 75 kWh/m². It is questionable whether the additional 11% reduction, achievable by replacing all infill panels, would ever be justifiable considering the disruption and potential loss of historic fabric.



Figure 6. Simulated Heating Energy Demand (kWh/m²) for case study 2. Hypothetical scenarios in grey, individual retrofit actions in orange and as-built in red

Occupants' perceptions of comfort

A semi-structured interview was conducted with the one occupant to gain an insight into their perception of the internal thermal comfort. The interview took place on the morning of 28/07/2017 in the kitchen with the sun shining outside. The occupant reported to be comfortable at the time of answering, whilst standing wearing jeans and long sleeve top, with a dry-bulb temperature of 23.7°C and a relative humidity of 52.2%. They found the house cold in winter. This they counteract by wearing thick jumpers. They describe the kitchen as the coldest room of the house, with the bathroom being OK and the sitting room being warm once the log burner was lit. They commented on how the heat from the log burner did not reach the rest of the house due to the sitting room being single storey and separated from the rest of the house by the thick stone chimney. Historically this would have been continually heated from both sides by open fires in both the living room and kitchen. Currently the flue of the log burner imparts little heat to this large thermal mass. In summer the downstairs rooms were reported to be comfortable or pleasantly cool; however, the upstairs room can overheat, especially the main bedroom, located above the kitchen.

The heating is a modern central heating system fuelled by liquefied petroleum gas (LPG). This was noted to be expensive but not a limiting factor, with heating being used as required from September to March, on a thermostat set to 21°C from 6am-10pm, and 15°C at night or when unoccupied. However, it was noted that the heating struggled to achieve a temperature of 19°C, this being blamed on the insufficient number of radiators. In the living room, the one radiator was felt to make little difference and the log burner is used every day in winter 1pm-10pm.

Even though the occupant found the house cold in winter and hot upstairs in summer they were happy living there and accepted that these were part and parcel of choosing to living in an old house in the countryside. They were content with their home and would not consider moving or requesting further retrofit actions.

Case study 3

Introduction

The third case study, now a private residence with two occupants, is located in the centre of Suffolk and is a Grade II listed former farmhouse, dating back to the 16th century (Historic England, 2014).

In the early to mid-20th century the timber-frame was overclad in cement render. The timber cill beams were encased in concrete and their interior faces painted with an impervious resin. In around 2005 most of the lath and plaster infill panels were replaced with rigid polyisocyanurate (PIR) thermal insulation. This detail exacerbates the cold-bridging of the historic timber-frame by the introduction of additional timber battening to take the plasterboard. The PIR insulation is not mechanically fixed or bonded and is left free-standing within the opening with large gaps around the sides in many instances.

On opening up the walls, it was observed that the expanded metal lath used to carry the cement render had in many places completely corroded away and the original oak laths

were in a state of advanced decay. Areas of the external cement render are cracked allowing rain penetration into the wall and building interior.

It is likely that the cement render was applied to reduce the need for maintenance of the previous lime render and the PIR insulation installed to improve internal comfort conditions and reduce energy consumption. However, neither were undertaken with a full understanding of the performance of the historic built fabric, and have now resulted in the poor current condition of the building.

The current ground floor slab is cast concrete finished in honed sandstone flags. The roof is thatched, insulated at ceiling level with mineral wool batts.

In situ measurements

Table 4. Results of in situ monitoring at case study 3, March - April 2017

U-value		
Material	Measured U-value (W/m²K)	Calculated U-value (W/m²K)
PIR insulation with cement external render & gypsum plasterboard lining	1.72	0.921
UK building regulations Part L1B	-	0.70 [†]
Airtightness		
	Air changes per hour @50 Pa	Air permeability @50 Pa (m³/(h·m²))
As measured 11/03/2017	18	19
UK Building Regulations Part L1A	-	5*
Hygrothermal Comfort		
	Percentage of hours comfort achieved[§] (%)	
Exterior	12	
Drawing Room [‡]	50	
Study	26	
Guest Bedroom	4	
Master Bedroom	38	

[†] U-value for existing building with change of use. In this case from farm building back to house

* An air permeability index is stated only for new constructions

[‡] No data recorded 05/11/2016-11/03/2017 due to failure of sensor

[§] Percentage of total hours where hygrothermal conditions comply with criteria defined by Givoni (Givoni, 1998)

The measured U-value of the PIR insulated infill panels is well below the calculated value, even when the thermal bridging of the timber frame is considered. This shortcoming is due to the poor design detail and installation of the rigid insulation and gypsum plasterboard. Both materials are ill suited to historic timber-frames with their irregular shapes and crooked angles. Internal thermography identified cold edges on most panel, highlighting

the deficiencies of this detail. Its poor airtightness is further corroborated by the pressure testing results and as a consequence the low number of hours where hygrothermal comfort are achieved. Measurements of timber moisture-content identified conditions at risk from biological attack from fungi and insect larvae, largely due to the use of non-moisture permeable materials and finishes.

Energy Use Simulations

The current situation was simulated using the measured u-values and airtightness. A further two simulations were undertaken using the calculated u-value to simulate the outcome potentially anticipated when the retrofit was undertaken. One used the measured airtightness, whilst the second assumed an improved airtightness with an air change rate of 0.5ac/h, a level seen to be achievable at case study 2.

Based on surviving infill panels in the west gable it is assumed that the house originally had lath and plaster infill panels. Two hypothetical pre-retrofit simulations were undertaken based on this assumption, one with the measured air change rate (0.9ac/h), and a second assuming an air change rate of 0.5ac/h.

Finally, four hypothetical retrofit actions were simulated. The first replaced all windows with triple glazing. As all current windows are already well fitting, it was assumed that this would not result in an increase in airtightness. The second assumed an increase in airtightness could be achieved by sealing all junctions between the gypsum plasterboard and timber-frame. The third replicates the current owners proposals to replace all PIR insulation with an equal thickness of sheep's wool, replace the external cement render with lime render on oak laths, and the internal gypsum plasterboard with lime plaster on oak lath. In the first instance, the airtightness is maintained at its current level, whilst the fourth and final simulation assumes that this revised construction would achieve an improved air

change rate of 0.5ac/h. As the roof is already well insulated with 200mm of mineral wool, this was not proposed as a retrofit action.



Figure 7. Simulated heating energy demand for case study 3 for a range of hypothetical pre and post-retrofit actions. Existing situation shown in red. Source: (Author's own, 2017)

Figure 7 shows that potentially, prior to the retrofit by the previous owner, the heating demand for the house could have been marginally better (-1%) than the current situation which has a building energy index of 92kWh/m². If the assumption that the original lath and plaster was more airtight than the current detail, then the house may even have been 10% more efficient. Obviously, this was not the intended outcome. If the thermal performance of the walls had achieved their calculated design value of 0.921 W/m²K, then a 26% or 35% reduction in heating energy demand would have been accomplished depending on the airtightness achieved.

The replacement of all windows with triple glazing makes little difference to the heating energy demand with the simulation results showing only a 2% reduction. This is to be expected, as most of the windows are already double glazed units in modern timber frames.

The simulation suggests that the new retrofit proposals of the current owner could achieve a 23% or 32% reduction in heating energy demand depending on the resulting airtightness. These results assume that the sheep's wool and lime plaster detail would achieve the calculated design u-value, which may not be the case, but is more probable than that of the rigid polyisocyanurate and gypsum boards due to the materials abilities to adapt to the irregularities of the timber-frame fully filling the infill panel.

Occupants' perceptions of comfort

Semi-structured interviews with both of the occupants took place on the 11/03/2017 with the sun shining. In summary, both occupants found the ground floor of the house to be comfortable in winter but slightly warm in summer. The converse was true with the upper floors, with both finding them comfortable in summer but in winter slightly cool in the case of the male occupant and cold in the case of the female. The difference in subjective thermal perceptions and preferences between the two occupants was evident from both reporting to feel comfortable during the interviews, despite the male occupant being outside in a t-shirt and trousers with a dry bulb temperature of 14.8°C and the female occupant reclining inside in a fleece, t-shirt and jeans at a temperature of 18.8°C. It was also notable in the female's study being kept slightly warmer than the rest of the house and the male's study on the top floor being slightly cooler.

It is interesting to note their thermal perceptions of the house do not appear to corroborate the hygrothermal monitoring. This is possibly due to the fact that the hygrothermal monitoring measured only air temperature and thermal comfort may have been achieved by radiation from the underfloor heating. It may however also indicate that the occupants are willing to accept lower comfort criteria in order to allow them to realise their ambition to live in a historic timber-frame building in a rural location.

With regards to heating and ventilation habits, the ground source heat pump was used almost continually throughout the year, except June and July, providing underfloor heating to the ground floor only. In addition, the log burner in the first floor drawing room was used every night throughout the year. Although the use of the log burner appeared to be at least in part a custom rather than being driven by thermal requirements. Electric convection heaters provide heating for the guest rooms. The windows to the master bedroom were always open and a window in the study was often opened. The rest of the windows were regularly opened especially in summer, with their use being governed principally by the need for fresh air, rather than as a means of regulating temperature.

Discussion

The results from the case studies highlight that it is possible to improve the thermal performance of the infill panels themselves if the incorporation of insulation is well detailed and installed. However, this in itself does not guarantee an improvement in the internal hygrothermal comfort conditions. The airtightness of other elements of the building must also be considered, as must the critical junction between the infill and the timber-frame. Ensuring that this detail is, and remains, airtight is a challenge that is evident in all three case studies. From a technical perspective, a pragmatic solution would be to apply either external or internal wall insulation that covers the timber-frame, thereby reducing the thermal bridging of the frame and improving airtightness. However this would obscure this building typologies defining feature, the exposed timber frame, which we have seen is fundamental to its cultural significance. Whilst it could be argued for a compromise, leaving one side exposed, this would either diminish the pleasure of the occupant or the public depending on the side it was installed. Even for those buildings, such as case study three, where the timber-frame is already overclad, great care would still be required to maintain the irregularities and angles of the external envelope which bear testament to the

true nature of the building's construction. In Germany where a greater degree of energy retrofit of this building typology has already been undertaken, some have spoken out in opposition claiming "Insulation is the death sentence for half-timbered houses (Dämmung ist das Todesurteil für Fachwerkhäuser)" (Stephan, 2014) due to loss of the internal character both visual and climatic resulting from the use of internal wall insulation (ibid). Given the case studies occupants' apparent willingness to accept the short comings of their timber-framed homes, perhaps this calls into question the need to focus on the thermal performance of their walls. The results of the simulations and associated in situ monitoring have highlighted that it is often apparently small measures, such as plastering ceilings and installing secondary glazing, which can have the most significant impact on reducing the heating demand of these historic timber-framed buildings. It is interesting to note that property with the least intervention and the highest achieved reduction in heating demand was the property owned by National Trust, The Oaks. This is perhaps not surprising that an organisation with a large property portfolio of historic buildings should achieve the best balance between intervention, outlay and payback.

Conclusions

It has been shown that timber-framed buildings occupy a special place in the cultural identity of the UK and more specifically England. They form a link to a rural, pre-industrialised past, their hand carved timbers bearing testament to the skill of the craftsman and the productivity of the land. In order to ensure their continuing survival, their ongoing use and occupation must be considered. A balance must be met between improving their energy efficiency and maintaining their historic and cultural value. However, the research presented in this paper questions the assumption that 21st century standards must be achieved. At the same time the differences between the three case studies highlight the need for the review of the retrofit of historic timber-framed buildings

on a case-by-case basis. The significance and condition of each building element must be considered to ensure that the proposed retrofit action does not produce unintended consequences and/or the unnecessary loss of historic fabric. To assist in this work further research is needed into possible solutions for the energy retrofit of historic timber-framed buildings and their potential impacts, both positive and negative on these buildings. At the same time, the work in this paper begins to question the influencing factors of occupant comfort and satisfaction in heritage buildings, opening a potential new field of investigation. By understanding both the technical parameters and the emotional connections with our built heritage it is hoped that these buildings can continue to feature in our collective cultural identity for generations to come.

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