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# INTERSTITIAL HYGROTHERMAL CONDITIONS OF LOW CARBON RETROFITTING DETAILS FOR HISTORIC TIMBER-FRAMED BUILDINGS IN UK.

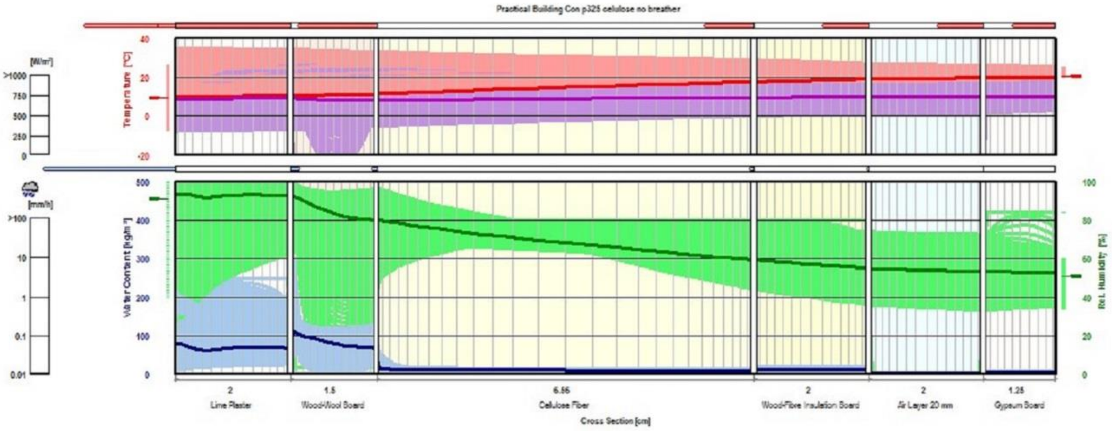

Fig 1: WUFI Pro5 simulation of English Heritage replacement infill detail.

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**Research summary**

Heritage buildings have often been considered off-limits when considering energy refurbishment projects, however rising energy prices and stricter legislation for public buildings mean that they can no longer be ignored (Todorović, 2012). In the case of historic properties refurbishment is a complex issue, involving aesthetic considerations in addition to technical issues (English Heritage, 2012). The hygrothermal behaviour of wall build-ups of traditional materials must also be fully understood in order to avoid problems of interstitial moisture, long term decay and overheating. Research in this area to date has focused on solid-walled masonry construction (Gandhi, Jiang , & Tweed, 2012; Mohammadpourkarbasi & Sharples, 2013; Scott & Rye, 2014) however little work has been conducted on historic timber-framed construction, the subject of the research presented in this paper. Whilst representing only a small percentage of the UK pre-1919 housing stock (approximately 66,000 in England (Nicol, Beer, & Scott, 2014); 1,200 in Wales and almost non-existent in Scotland (Naismith, 1985) and Northern Ireland (Gailey, 1984)), many historic timber-framed buildings have stood for hundreds of years and form an important element of UK heritage. Inappropriate introduction of thermal insulation can cause unintentional negative impacts, including increased moisture content and interstitial condensation leading to the deterioration of the built fabric. Using WUFI Pro5 transient heat and moisture simulation software, the interstitial temperature, humidity and moisture conditions within traditional and retrofitted wall build-ups have been simulated. This paper presents the results of these simulations which would initially suggest that current proposed retrofit details do not pose a serious threat to timber-framed buildings. Further simulation, experimental and building monitoring, is however required and this is planned as part of this on-going research programme.

**Keywords**: Timber-framed, interstitial, hygrothermal, retrofit, simulation, UK

## 1. Introduction

In 2008 the UK government committed itself to reducing national greenhouse gas emissions by at least 80% by 2050, taking 1990 emissions as a base line ("Climate Change Act," 2008). In 2013, buildings were responsible for 37% of these emissions (Commitee on Climate Change, 2014) and it has been estimated that 70% of the current UK housing stock will still be in use in 2050 (Lowe, 2007). When the embodied energy of these existing buildings is added to the social, environmental, economic and cultural impact of their replacement it becomes clear that their refurbishment is the preferable solution (Power, 2008). This is even more so when considering heritage buildings, however, their refurbishment is a challenging issue, involving aesthetic and philosophical considerations in addition to complex technical issues (English Heritage, 2012). For this reason heritage buildings have until recently not been considered candidates for energy retrofitting, however, rising energy prices and stricter legislation for public buildings means that they can no longer be ignored (Todorović, 2012). One technical issue is the hygrothermal behaviour of wall build-ups in buildings of traditional materials. This must be fully understood in order to avoid problems of interstitial moisture, long term decay and overheating. Research to date has focused on solid-walled masonry construction (Gandhi et al., 2012; Mohammadpourkarbasi & Sharples, 2013; Scott & Rye, 2014) however little work has been conducted on timber-framed construction. This research therefore aims to explore this previously under-researched area, starting with the digital simulation of interstitial hygrothermal conditions.

### *1.1 History of Timber-framed buildings in UK*

Timber construction can be traced back to the earliest British dwellings (Prizeman, 1975) where central poles supported a basket like structure of branches and twigs, often with a covering of turf. Following improved felling methods, construction in solid logs became possible in the Bronze Age. The only surviving example of this construction can be seen at the church of St Andrews, Greensted, Essex (Prizeman, 1975). As timber became less plentiful, methods requiring less timber were developed in the form of the timber frame. The earliest surviving timber framed building dates from the 13$^{th}$ Century (Harris, 2010). Building in timber framed continued as a common construction method until the late 18$^{th}$ early 19$^{th}$ Century (Harris, 2010). The size of the timbers varied according to the size of structure and the available local timber. The infill of the frames consisted of oak laths and plaster, stone slabs, fired brick or woven timber plastered with an earthen render, known as wattle and daub. One of the earliest examples of the use of wattle and daub in Britain can be found at an Iron Age settlement in Glastonbury (Davey, 1961). In Roman times, Vitruvius bemoaned the use of this material. In his second book, chapter VIII paragraph 20, he writes; “As for “wattle and daub” I could wish that it had never been invented. …it is made to catch fire, like torches. And, in the stucco covering, too, it makes cracks from the inside by the arrangement of its studs and girts. For these swell with moisture as they are daubed, and then contract as they dry, and, by their shrinking, cause the solid stucco to split.” (Vitruvius & Morgan, 1960). Despite these problems, examples of timber-framed buildings with wattle and daub infill can still be found to this day.

*1.2 Timber-framed buildings in UK today*

Today it is estimated that there are around 66,000 timber-framed buildings in England (Nicol et al., 2014) and around 1,200 in Wales (Smith, 1988). The building typology is however almost non-existent in Scotland (Naismith, 1985) and Northern Ireland (Gailey, 1984) although it was once common to these parts being referred to by the Venerable Bede in his *Historia Ecclesiastica III, xxv,* as *Mos Scotorum* or the “Scottish Manner” (Bede & Giles, 1843).

*1.3 Low Carbon Retrofitting of historic timber-framed buildings*

As with the conservation of all historic buildings, great care must be taken to minimize the loss of original fabric. In addition to the timber, this may include original infill material and finishes, including in some cases wall paintings. The Society for the Protection of Ancient Buildings (SPAB) advises that where more than 50% of the panel is in sound condition, repair or part renewal should be undertaken (Reid, 1989). This is followed by the caveat that on-site examination by an expert should always be sought.

Where complete renewal of the panel infill is required due to extensive damage, decay, repair of surrounding timbers or the removal of inappropriate modern materials, then there opens up the opportunity of retrofitting an alternative with a lower thermal transmittance (U-Value). Advice as to possible replacement details is given by English Heritage (McCaig & Ridout, 2012; Ogley, 2010) and SPAB (Reid, 1989). The general consensus in the conservation of historic building envelopes, is the need for the constructions to allow the movement of moisture or “breathe” (Hughes, 1986). It is therefore surprising that Reid’s SPAB technical pamphlet includes details with vapour barriers, closed cell foam insulation and cement render. For this reason the pamphlet is currently in the process of being revised. Where the replacement of the infill material is deemed to be an unacceptable loss of historic fabric, English Heritage proposes the alternative of internal insulation (Ogley, 2010).

*1.4 Potential risks of retrofitting*

The inappropriate introduction of thermal insulation could potentially cause unintentional negative impacts, including increased moisture content and interstitial condensation leading to the deterioration of the built fabric. The two biggest threats to timber-framed construction are insect infestation and fungal decay, of which, the susceptibility to both increases as the moisture content of the timber rises. The threshold hygrothermal conditions for common insects and fungi are listed in Table 1.

Table 1 Hygrothermal conditions for common UK biological timber threats (McCaig & Ridout, 2012).

| | **Biological threat** | **Moisture content (%)** | **Temp (˚C)** |
|---|---|---|---|
| Beetles | Powderpost (*Lycus linearis Goeze & Lyctus brunneus*) | 8-25 | 26 |
| | House Longhorn (*Hylotrupesw bajulus*) | 15-25 | 20-30 |
| | Furniture or “Woodworm” (*Anobium punctatum*) | >12 | 22 |
| | Deathwatch (*Xestobium rufovillosum*) | >15 | >10 |
| Fungi | Dry Rot (*Serpula lacrymans)* | >25 | 17-23 |
| | Oak Rot (*Donkioporia expansa*) | >28 | 5-40 |
| | Cellar Rot (*Coniophora puteana*) | >25 | 20-32 |

## 2. Research objectives

This research aims to study the hygrothermal performance of details for replacement infill panel currently proposed by heritage bodies, in addition to a further 3 details developed by the authors in collaboration with Tŷ-Mawr Lime Ltd. By doing so it is hoped to evaluate the risk of unintentional negative impacts on the historic fabric. This paper presents the results of the digital simulation of interstitial hygrothermal conditions of each of these details. Further simulation and physical monitoring are planned as part of this ongoing research programme.

## 3. Methodology

A total of 13 retrofit details were studied (Table 2). A thickness of 115mm was assumed for the timber-frame in each detail.

Table 2. List of reviewed details

| Code | Source | Description | U-Value (W/m²K) |
|---|---|---|---|
| S1a | SPAB fig.12 | Wattle and Daub + internal and external lime plaster. | 2.83 |
| S1b | SPAB fig.12 | As S1a but with foil backed plasterboard in place of internal lime plaster | 2.53 |
| S2 | SPAB fig.13 | 60mm glass wool + lime plaster on expanded metal lathe. | 0.67 |
| S3 | SPAB fig.14 | Lime render, 50mm wood wool, 25mm glass wool, vapour barrier (VB), 25mm wood-fibre, internal skim coat. | 0.63 |
| S4 | SPAB fig.17 | Lime render, 50mm wood wool, 25mm extruded polyurethane, VB, internal gypsum plaster. | 0.62 |
| S5 | SPAB fig.18 | Half brick nogging, 12.5mm EPS + Internal lime plaster. | 1.14 |
| E1a | EH-1* pg325 | Lime render, 15mm wood wool, Breather membrane (BM), 54mm cellulose fibre, 20mm wood-fibre board, VB, service void + plasterboard. | 0.42 |
| E1b | EH-1* pg325 | As E1a but with no BM or VB | 0.42 |
| E2 | EH-2ǂ Fig.18 | Historic infill retained, BM, 50mm wood-fibre to inside face + lime plaster. | 0.64 |
| E3 | EH-2ǂ Fig.19 | As E2 but with 20mm air-gap in place of BM + plasterboard | 0.59 |
| T1 | Tŷ-Mawr | 115mm hemp lime + internal and external lime plaster. | 0.84 |
| T2a | Tŷ-Mawr | 2x40mm cork board + internal and external lime plaster. | 0.48 |
| T2b | Tŷ-Mawr | As T2 but with 2mm lime plaster between cork boards. | 0.48 |

*EH-1 (McCaig & Ridout, 2012)
ǂ EH-2 (Ogley, 2010)

Of these 5 were taken from the SPAB Technical Pamphlet “Panel infilling to timber-framed buildings” (Reid, 1989), 1 from English Heritage’s book “Timber” from their series “Practical Building Conservation” (McCaig & Ridout, 2012), 2 from English Heritage’s pamphlet “Insulating timber-framed walls” in their “Energy Efficiency in Historic Buildings” series (Ogley, 2010) and a final 3 details developed by the authors in collaboration with the supplier of ecological building materials Tŷ-Mawr Lime Ltd. Eleven of the details are for replacement infill panels, whilst the remaining two are for internal insulation as suggested by English Heritage (Ogley, 2010).

### *3.1 Simulation with WUFI Pro5*

The 13 details were simulated with WUFI (*Wärme und Feuchte Instationär*) Pro5 transient heat and moisture simulation software developed by the Fraunhofer Institute. A weather file for Hereford, UK, created with Meteonorm software, was used for the external climate, with the internal climate being calculated according to BS EN 15026:2007 as recommended by the European SUSREF guidelines for modelling refurbishment of external walls (Peuhkuri et al., 2011). An orientation of 45˚ (South West) was chosen to simulate maximum effect of wind driven rain. All material data was taken from the existing software databases, except for hemp-lime which was supplied by A. Evrard (Evrard, 2008). The simulations were set to run from 1st October for a period of three years.

#### *3.1.1 Risk of interstitial condensation*

Following the simulations the interstitial temperatures and dew-point temperatures were compared to identify if temperatures drop below dew-point thereby producing the potential risk of interstitial condensation.

*3.1.2 Review of total water content*

The total water content of each construction was reviewed. The period taken for annual moisture equilibrium to be achieved, i.e. for built-in construction moisture to dry-out, was calculated. This was done by comparing the first and second year results and identifying the point when the difference between the two is less than 0.1kg/m$^2$. The results are presented in Fig 2. The total water content for the second year of simulation, i.e. once annual moisture equilibrium has been attained, is presented in Fig 3.

*3.1.3 Risk of biological attack*

The hygrothermal conditions in each layer were then compared against the criteria presented in Table 1, to assess the potential risk of biological attack of timber in contact with the layer. For this analysis the initial drying period was ignored. For those constructions with drying periods longer than a month, the risk during this period was reviewed separately.

To convert the gravimetric moisture content (%) quoted in Table 1, to gravimetric water content (kg/m$^3$) produced by the simulation, the following formulae were used:

$$u = \frac{M_w}{M_t} \quad \text{and} \quad M_t = M_w + M_{dry}$$

Where:

u = Gravimetric moisture content (%)
$M_w$ = Gravimetric water content (kg/m$^3$)
$M_{dry}$ = Dry density of timber (kg/m$^3$)

Giving $$M_w = \frac{M_{dry} \times u}{1-u}$$

As the majority of UK timber-framed buildings are primarily constructed of oak, a dry density of 720kg/m$^3$ was used (TRADA, 2015).

**4. Results and analysis**

*4.1.1 Risk of Interstitial Condensation*

The results of the simulations would suggest that none of the proposed constructions had the risk of interstitial condensation. At times the interstitial temperature did drop close to the dew-point but at no time did it drop below.

*4.1.2 Total Water Content*

*4.1.2.1 Drying time*

The time taken to reach annual moisture equilibrium is presented Fig 2. This shows that the wattle and daub (S1a&b) and the hemp-lime (T1) have the longest drying times, the hemp lime (T1) taking 118 days, almost 4 months. When the start date of the simulation was moved from 1st October to 1st June this reduced the drying times by 63% for S1a, 50% for S1b and 54% for T1.

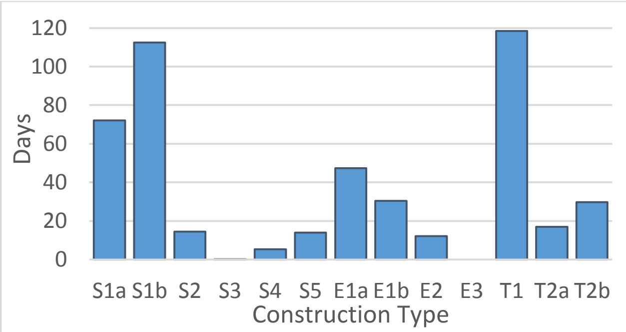


Fig 2: Drying period for constructions.

*4.1.1.2 Total Water in 2nd Year*

The total water content for the second year of simulation, once annual moisture equilibrium has been attained, are presented in Fig 3. This shows that the two internally insulated details as proposed by English Heritage (E2 & E3) have higher total water contents for approximately half the year. Additional simulations showed that total water content increases with insulation thickness. This is due to the cooling of the external wattle and daub reducing its ability to dry out.

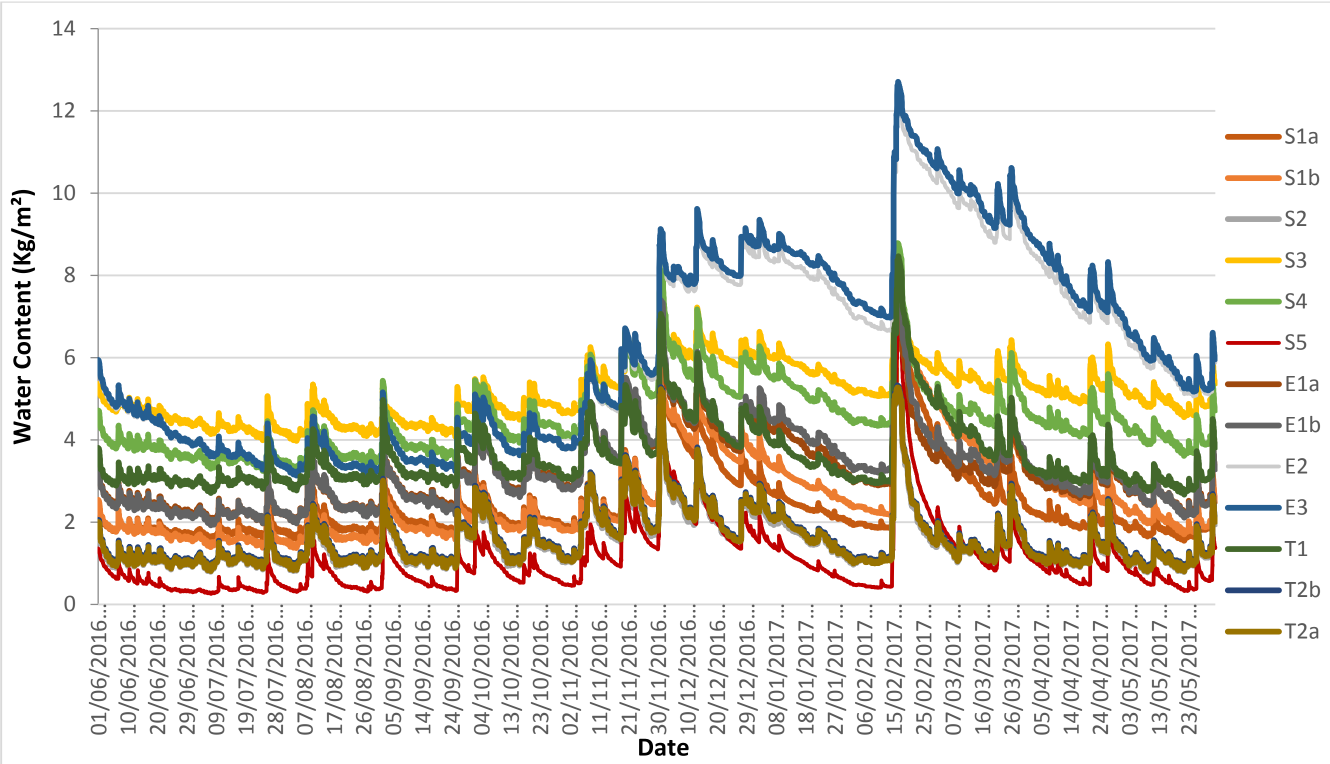


Fig 3: Total water content of constructions in second year of simulation.

No potential threat of interstitial condensation was identified by these additional simulations. Even when internal insulation was increased to 200mm there remained a difference between temperature and dew-point of +0.25˚C.

The second highest total water content was seen in the SPAB details with artificial insulation used in conjunction with wood-wool and vapour barriers (S3 & S4). Interestingly the hemp-lime construction (T1), once it has dried, has a similar total water content to the English Heritage replacement infill details (E1a&b).

There is conflicting results with regards to the inclusion of membranes in the build-up. In the case of E1a&b the introduction of internal vapour barrier and external breather membrane (E1) results in marginally lower water content during winter months. However, the introduction of a vapour barrier on the inside of a traditional wattle and daub wall (S1b) has the inverse effect, with higher water content in winter. The four details with the lowest total water content are the SPAB detail with glass fibre, metal lathe and lime plaster (S2), the two cork details (T2a&b) and the SPAB detail for insulating retained brick nogging (S5). The latter being the lowest. The addition of 2mm of lime mortar between the cork layers in T2b made negligible difference, with an increase of 0.05kg/m$^2$ total moisture content.

That brick infill has the least total water content would appear to go against anecdotal evidence that suggests that brick nogging is a poor infill material, holding damp and promoting decay (Harris, 2010; Reid, 1989). This highlights the fact that the simulation is only concentrating on the moisture moving between, and held within, the homogenous, continuous layers of the infill materials. It is not reflecting the moisture movement and accumulation that could occur at the junction with the timber frame, nor what occurs when layers are heterogeneous and non-continuous as in the case of the brickwork.

*4.1.3 Risk of Biological Attack*

The comparison of the simulated interstitial hygrothermal conditions and the conditions favourable for the growth of fungi and infestation by insects (Table 1) suggests that the only potential threat would be from the Death Watch Beetle (*Xestobium rufovillosum*). Given that this beetle can only infest sapwood and wood already modified by fungi (McCaig & Ridout, 2012), the threat is minimal. However the number of hours per year that favourable conditions exist is presented in Fig 4.

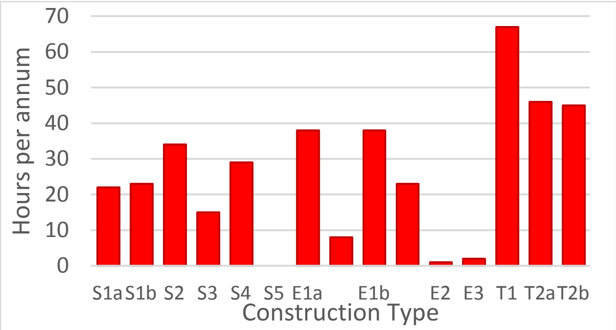


Fig 4 Presence of hygrothermal conditions favourable for Death Watch Beetle infestation.

The construction with the greatest potential risk of attack is the hemp-lime (T1) with 67 hours per annum of favourable conditions in the external lime plaster layer. These hours are spread over 15 instances, the duration of which range from 1 to 14 hours, with an average duration of 4.5 hours. During the separately studied drying period an instance of prolonged favourable hygrothermal conditions lasting 39 hours was identified.

The cork board details (T2a&b) have the second highest potential risk of attack with 46 and 45 hours respectively, spread over 10 instances, with a 4.6 hour average duration. In the case of the English Heritage replacement infill details (E1a&b) the potential risk spreads from the external render, into the underlying wood-wool board. Detail E1a with an external breather membrane has 8hrs of favourable conditions within this secondary layer, whilst that without a membrane (E1b) has three times this with 23hrs spread over 5 instances with a duration ranging from 2 to 9 hours.

## 5. Future Implementation

It is important to stress, as previously mentioned, that the simulations presented in this paper represent the moisture movement between idealized, homogenous, continuous layers of the infill materials. They do not reflect the moisture movement and potential accumulation at the junction with the timber frame, nor the reality of heterogeneous and non-continuous layers present in actual constructions. For this reason simulation with WUFI 2D-3 and physical monitoring is essential. It is hoped that this further research will enable the production of best practice details.

## 6. Conclusions

The initial results of the simulations have not identified any proposed infill details that create hygrothermal conditions that pose a major threat to the surrounding timber-framed construction. Within the details studied there was a wide range of resulting total water contents, however these did not necessarily translate into conditions favourable for biological attack. Care should be taken with the use of internal insulation due to the resulting higher total water content and increased risk of intestinal condensation. As would be expected, techniques with high built-in moisture, (wattle and daub and hemp-lime) have long drying periods. Care should therefore be taken as to the timing such work.

As previously mentioned further research is required and is planned as part of this ongoing research.

**7. Acknowledgments**

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