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Evaluating Incidental Thermal Performance Improvements of a Historic Timber-Framed Building in Central Hereford

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Abstract. As we strive to decarbonise our historic built environment, a balance must be struck between technical, aesthetic, philosophical and economic concerns. Compromises must be made and opportunities seized. At the same time, evaluation allows us to assess decisions previously made and reflect on their outcomes. This paper presents the evaluation of the refurbishment of The Old Mayor's Parlour, Church Street, Hereford, a historic timber-framed building now used as a gallery and exhibition space. The conservation work undertaken was not specifically envisioned as an energy retrofit, however the necessary replacement of failing concrete block infill, the legacy of a 1970s renovation, allowed improvements to be made to the thermal performance of the external envelope. Environmental monitoring and digital simulation have been used to assess the impact of these interventions. In situ U-value measurements show the success of the replacement infill panels and associated internal lining, although digital energy simulations suggest a limited improvement to the building's overall energy efficiency. At the same time thermography suggests a potential threat of increased condensation risk to the uninsulated ornate 17th century plaster ceiling. The results of this paper show the risk of unintended consequences and the challenges faced by sustainable building conservation.

1. Introduction

The retrofit of our existing building stock has been identified as a key factor in achieving international goals for mitigating climate change [1]. This has been reflected in policy by both the EU [2] and the UK governments [3]. Although in the UK historic buildings and those of a traditional construction are not required to fully comply with the energy efficiency requirements of the building regulations [4, 5], they must still aim to “improve energy efficiency as far as is reasonably practicable” [6]. At the same time, building owners and occupants wish to improve the thermal comfort of their properties and reduce heating bills. As such, both the extent and detail of any retrofit remains at the discretion of the building owner. Whilst it is hoped that they will seek advice from qualified professionals, the lack of knowledge in the construction industry with regard to energy retrofit in general [7], and especially related to historic and traditional buildings [8], combined with a reduction in historic environment specialist within local authorities [9], means that too often they do not. By undertaking the evaluation of those buildings where retrofits have been undertaken, we can assess their success and apply those lessons learnt to future projects. Research into the energy retrofit of historic buildings in the UK has to date focused on solid masonry construction [10-12], with little research covering the 68,000 timber-framed buildings that form an integral part of the UK and



specifically England's cultural identity[13]. This paper therefore begins to explore this previously under-researched area with the evaluation of one such building.

2. Case Study

2.1. Introduction.

The Old Mayor's Parlour (OMP), 24 Church Street, Hereford is a gallery space owned by the Church Street Charitable Trust, together with the adjacent property, 25 Church Street (Figure 1). This building was selected as a case study as part of a larger research project [13] due to the use of a replacement infill panel detail suggested by Historic England in their "Practical Building Conservation" series [14] a popular reference source for conservation professionals.



Figure 1. Nos.24 and 25 Church Street, Hereford. Source: (Author's own, 2016)



Figure 2. Detail of plaster ceiling, Old Mayor's Parlour. Source: (Author's own, 2016)

The building is divided into three separate entities; The OMP on the first floor of 24 Church Street (the right-hand gable in Figure 1), accessed via a staircase within 23 Church Street; "Rocket" café on the ground floor of no.24; and "Layers" women's clothes store at no.25, with a sales area on the ground floor and storage and office on the first. The interconnecting door between the OMP and the Layers' storage area was locked shut at all times and was sealed during pressure testing.

2.2. History

According to the designation description, the buildings date from the early 17th century [15], however, other sources state that the buildings origins are 14th century [16, 17]. The original description by The Royal Commission on Historical Monuments records the building as probably built early in the 16th century but with a stone-built cellar under the north part of the building, containing 15th century doorways [18]. The east façade onto Church Street is timber-framed at first floor with underbuilding and 20th century shopfronts. It is claimed that it once was used by the *Custos Rotulorum*, the keeper of the rolls, and the Vicars Choral (the men of the Cathedral Choir) [17]. Its most notable feature is the ornate early 17th century plaster ceiling to the gallery space (Figure 2) and a fresco of what is believed to be Hereford Castle [17]. The building was saved from demolition in 1969 with help from Ivor Bulmer and the Ancient Monuments Society and had recently been refurbished [16, 19].

2.3. Retrofit

The first phase of the most recent refurbishment work consisted of internally lining the east first floor façade of the OMP with polyisocyanurate (PIR) insulation and wood wool boards, finished in gypsum plaster. During this first phase of work it was discovered that the infill to the timber-frame was very loose modern concrete blockwork, rendered with a cement lime render externally and gypsum plaster internally [19]. It was therefore decided that this would require replacement during a second phase of work. When this took place, the aforementioned concrete block infill was removed from the timber-

framed east façade of both the OMP (no.24) and no. 25 and replaced with wood-fibre insulation based on the previously mentioned detail published by Historic England [14] (Figure 3).

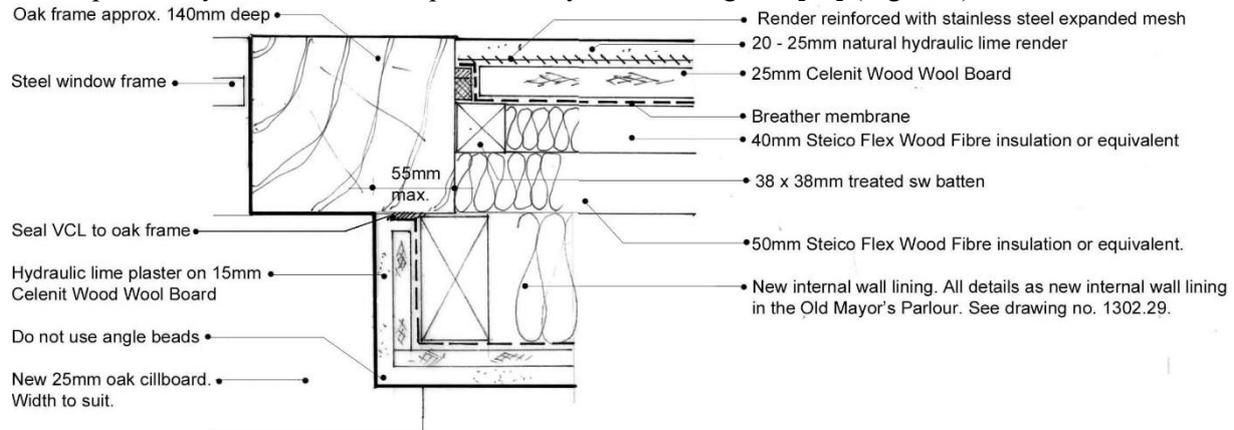


Figure 3. OMP replacement panel infill detail with internal lining. Source: (Project Architect, 2014)

At the same time an internal lining to the first floor of no.25 was inserted using the same detail as that used for the OMP but with mineral wool insulation in the place of PIR [19]. Whilst installing the replacement panel infill detail, the conservation contractor found the wood fibre insulation difficult to use due to its friable nature and the challenge of accurately cutting a board material to fit the irregular timber-frame [20]. In addition to these technical issues, in the opinion of the author, the regularity of the finish created by the board substrate lacks the character of panels with a wattle or oak lath background.

3. Methodology

In order to evaluate the performance of the retrofit actions, the following monitoring was undertaken; in situ U-value measurements, thermography, pressure testing and monitoring of internal hygrothermal comfort conditions. Measured data was then used to perform digital energy demand simulation. There follows a brief description of the methodologies employed. Where possible the relevant British and International standards were followed and best practice guidelines consulted in order to maximise the validity of the data collected.

3.1. In Situ U-value.

Two infill panels on the retrofitted east facade were monitored following BS ISO 9869-1:2014 [21], one in the OMP and the other in the first floor office of no.25. Huxeflux HFP01 heat flow plates were held by pressure against the wall surface with building props and flexible plastic clips. Petroleum jelly and plastic film was used to ensure a continuous contact between plates and wall. The outputs from the plates were connected directly to an Eltek® Squirrel® data logger with the voltage recorded at 5 minute intervals. The internal and external ambient dry bulb air temperatures (°C) were measured with thermistors also wired directly back to the datalogger, with readings at the same frequency. The external temperature thermistor was protected from direct solar radiation by a ventilated, plastic and foil cover. As per the BS, only data collected one hour after the surface had passed into shade was utilised. The in situ U-value monitoring was undertaken between 18/02/2016 and 10/03/2016, with a measurement period of 21 consecutive days.

3.1.1. Assumptions and limitations. The panels can be classified as “quasi-homogenous” according to the BS’s definition [21], however overall the facade is heterogeneous with the timber-frame forming a thermal bridge. The BS states that heat flux sensors “shall not be installed in the vicinity of thermal bridges, cracks and similar sources of error” [21]. No distance is specified, however, the surrounding timber-frame constitutes such a source of error. This is a problem common to all timber-frame infill panels in general, therefore direct comparison between panels can be made, however care should be

taken in comparing these results with those of solid wall constructions [10, 22, 23], without timber-frames and the associated errors.

3.2. Pressure Testing.

The air permeability index ($\text{m}^3/\text{hr}/\text{m}^2$) and air change rate (/hr) were measured following BS EN ISO 9972:2015 [24]. All intentional openings in the building envelope were sealed and all doors and windows closed. A Minneapolis Blower Door, was used to depressurise the building, with building pressure and the fan pressure measured using magnehelic analogue pressure gauges. The gauges were zeroed prior to commencing depressurisation. Measurements were taken at regular intervals both up until a $>50\text{Pa}$ pressure difference had been achieved and as pressure returned to normal.

Pressure testing took place on 11/03/2016. Due to the compartmentalised configuration of the property, only the OMP, located on the first floor, was pressure tested. The Minneapolis® blower door was inserted in the doorway between the semi-external staircase and the gallery. The tube measuring external air pressure was extended down and out onto the street. It cannot be assumed that the dividing floor between the gallery and the cafe below has been designed to act as an air barrier. Additional leakage through this element must therefore be considered when reviewing the results.

3.3. Thermography

Given that no British Standard exists for infra-red thermography of buildings, the Building Research Establishment (BRE) [25] and Historic Environment Scotland's (HES) [26] guides were consulted in the creation of this methodology. The BRE guide recommends a minimum temperature difference between inside and outside of 10°C or 5°C if the building is mechanically pressurised or depressurised [25]. It is recommended that this temperature difference is maintained for a 24 hour period prior to the commencement of the monitoring, with a variation of external temperature of $>\pm 2^\circ\text{C}$. This in reality is difficult to achieve. The HES guidance is less stringent, only stating that a "significant temperature difference" is achieved, with a recommendation of a minimum difference of 5°C [26]. The temperature differences achieved are stated with the results. In order to minimise the effects of direct solar radiation and to maximise the temperature difference, thermography was undertaken just prior to sunrise on 11/03/2016, at 06:00 for the external and 06:30 for the internal. A FLIR® B250 thermal imaging camera was used for both. Using the Minneapolis Blower Door the OMP was pressurised during the thermography of external surfaces, and depressurised for that of the internal surfaces.

3.3.1. Assumptions and limitations. Care must be taken with variations in surface emissivity, thermal influences from building services and genuine variations in temperature which must be expected due to the physics of heat flow, such as at the corner of walls, and the junction between floors and ceilings [25, 26]. Care must also be taken over reflective surfaces such as glazing, as measurements will be of the objects reflected and not the surface itself [26].

3.4. Internal Hygrothermal Comfort.

According to ISO EN 7726: 2001 [27] sensors for monitoring hygrothermal comfort should be mounted at 0.1m, 1.1m and 1.7m above finished floor level in the centre of the space or close to the typical location of the occupant(s). This is however impractical for long-term measurements within an occupied space, where sensors would be intrusive and subject to possible interference. Instead, the sensors were located in discrete locations, selected to minimise both the influence of localised microclimates and inadvertent disturbance by the occupants. Whilst not ideal, this methodology enabled monitoring to occur over a longer period of time undisturbed. For the first three week period, between 18/02/2016 – 10/03/2016, TinyTag Ultra 2 TGU-4500 sensors were used. Due to concerns from the building's trustees over their visual intrusion during exhibitions, subsequent monitoring was continued with Maxim Hygrochron iButton DS1923 Sensors. With a similar accuracy but a reduced resolution (0.5°C and 0.6%), at less than 20mm diameter they are unobtrusive. These were left in place until July 2017 with the intention of obtaining at least one calendar year of measurements. Unfortunately, the capacity of the sensors memory was exceeded on the 03/06/2016 having recorded

only three months of data. Two locations within the OMP were monitored one to the east end and one to the west. In no. 25 Church Street a further two locations were monitored, one within the WC and the other in the office, both of which are located on the first floor to the east of the property.

The measurements recorded were then used to assess the hygrothermal comfort conditions by plotting the results on a bioclimatic chart, as developed by Givoni [28] who defines the comfort zone between 17°C and 27°C, with a range of relative humidity between 20% and 70%.

3.5. Digital Energy Demand Simulation.

Dynamic digital energy simulation was carried out using DesignBuilder Version 4.2.0.54. The weather file was created using Meteororm version 6.1 using the time period 1996-2005. Each retrofit action was simulated separately, in addition to the hypothetical actions of insulating the roof and installing secondary glazing. In addition, scenarios combining retrofit actions were also simulated. As the OMP is located on the first floor between adjacent buildings, these and the ground floor were modelled as adiabatic volumes.

4. Results and Analysis

4.1. In situ U-Value monitoring.

The measured U-values are presented in Table 1. When the standard deviation is considered, these are similar those calculated according to BS EN ISO 6946:2007. It is to be expected that the measured and calculated U-values are similar as, unlike measurements of historic or non-conventional constructions, these infill panels are of standard layers of know materials. These U-values are well within the standards for new thermal elements for existing buildings as defined by the Building Regulations [5].

Table 1. OMP and No.25 Church Street. Measured and calculated U-values.

	Measured U-value (W/m ² K)	Standard deviation (W/m ² K)	Calculated U-value (W/m ² K)
Old Mayor's Parlour	0.11	±0.04	0.13
No 25 Church Street	0.11	±0.03	0.17

4.2. Pressure Testing.

Based on the readings measured¹ the calculated air permeability index was 17.6 m³/h/m² and air change rates were 22.5 /hr@50 Pa and 1.12 /hr unpressurised. As such the building does not achieve the 10 m³/h/m² air permeability index required by building regulations for new-build [29] and is higher than the average air change rate for pre-1900 UK buildings of 12.3 ac/hr@50 Pa [30]. It is however similar to other historic timber-framed buildings measured by the authors [13]. The weakest areas are most probably the windows and the floor separating the OMP from the café below.

4.3. Thermography.

The recommended temperature difference of >10°C was achieved for both the external and internal thermography as presented in Table 2.

Table 2. Temperature difference for thermography at The Old Mayor's Parlour, 11/03/2016

	External Temp. (°C)	Internal Temp. (°C)	Temp. difference (°C)
External Thermography	2.4	20.4	18
Internal Thermography	0.4	22.9	22.5

¹ (R²) of the best-fit line of the ln(flow) against ln(pressure difference) = 0.9781 showing a good degree of accuracy.

Figure 4 shows that the new infill panels are performing better than the surrounding timber-frame. The weak points of the façade are the windows and some joints between the timbers of the frame, especially around the first floor window.

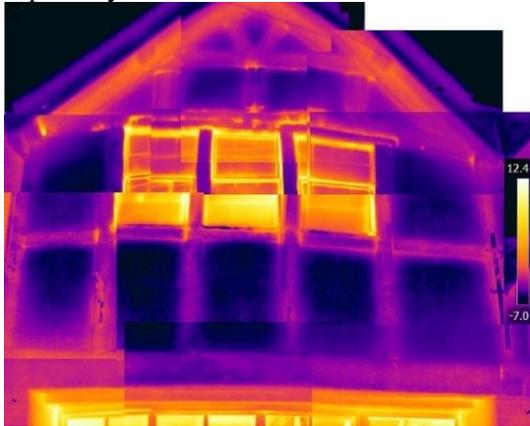


Figure 4. Thermography of east façade.

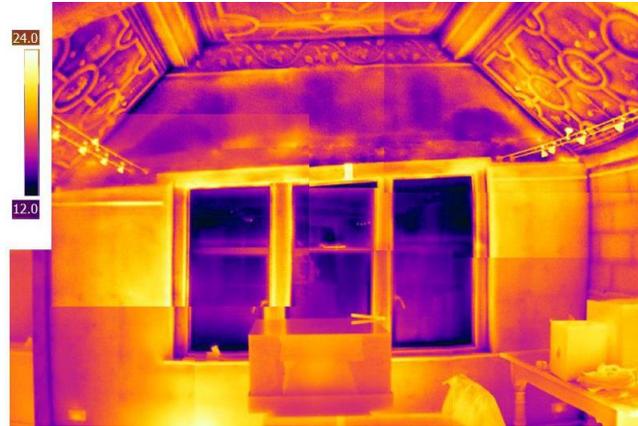


Figure 5. Internal thermography of east façade.

Figure 5 shows the efficacy of the internal lining, with no noticeable cold bridging or temperature difference across the internal surface. The upper portion of the wall with no internal lining is however cooler, with marked cold spots in the recesses of the historic plasterwork. Whilst the physics of heat flow dictates that recesses and junctions will naturally be cooler, this image still raises concern over the decision not to internally line the upper portion or introduce roof insulation. The rationale of minimising intrusion and damage to the historic fabric is understandable but potentially, over time, may lead to the concentration of condensation and accelerated decay. This issue is explored further below.

4.4. *Hygrothermal monitoring.*

It was known that the OMP would be unoccupied and unheated during the first measurement period. It was however expected that the office and WC of No. 25 Church Street, both in daily use, would have some degree of heating. It was therefore surprising to see from the results that neither of these spaces were heated, with temperatures in the WC closely following those in the OMP at around 10°C. Temperatures in the office were a little higher, occasionally exceeding 15°C, probably due to heat rising from the shop below but fail to achieve levels of comfort. Whilst the author has encountered similar situations in a developing country or fuel poor households, it is perhaps unexpected in a commercial premises in Hereford. The results for all spaces show that comfort conditions were not achieved during office hours. Although this lack of heating reduced energy consumption and associated costs, it may create unintended consequences such as increased condensation and accelerated deterioration of interior finishes and building fabric.

The second stage of monitoring 10/03/16 – 04/06/2016 showed that once in use for exhibitions, the temperatures in the OMP did exceed 17°C for parts of the working day (Figure 6). However, the office of No.25 did not begin to enter the thermal zone until the external temperatures rose in early May.

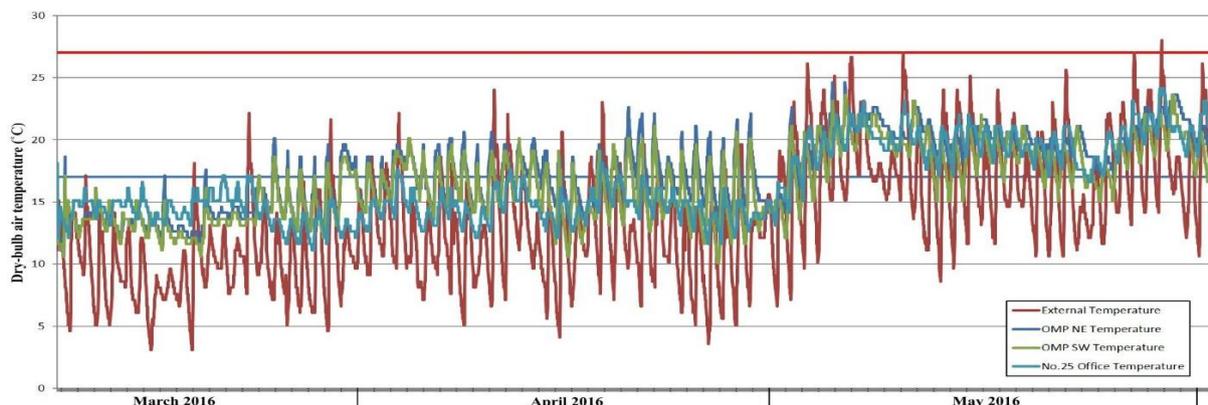


Figure 6. Dry-bulb air temperatures 10/03/2016 to 04/06/2016. Source: (Author's own, 2017).

During opening hours (09:00-17:00) over the four and a half months of monitoring, hygrothermal comfort was achieved 50% of the time in the east end of the OMP, 55% of the time at the west end but only 28% of the time in no.25. The difference between the east and west end of the OMP may be due to the door to the semi-external staircase being located towards the east, although the electric heater is also located at this end of the room.

As noted previously, the lack of insulation to the roof raised some concern over the possible concentration of condensation on the cold surface of the 17th century decorative plaster ceiling. This would most likely under conditions of high vapour pressure, coupled with a large diurnal temperature variation. The highest vapour pressure recorded in the OMP was 1557Pa, occurring at 15:30 on 12/05/2016 at a dry-bulb temperature of 23°C. Tracing this vapour pressure across on the psychrometric chart, condensation would occur at a dew point temperature of 13.5°C. Within the following 24 hours, the minimum internal dry-bulb temperature was 18.6°C and the minimum external temperature 11.1°C. As such, it is possible that the internal surface temperature of the ceiling could have dropped, in places, below the dew point temperature and condensation may have occurred. Equally, on the day with the largest diurnal temperature oscillation, the 28/04/2016, a maximum vapour pressure of 913Pa was recorded at a temperature of 17°C. The internal dry-bulb temperature then dropped to 11.6°C with a minimum external dry-bulb temperature of 5.6°C. Given that the dew point temperature for the maximum vapour pressure measured (913Pa) would be 5.7°C, there again exists a small possibility that conditions for condensation may have occurred. In order to prove this, further monitoring of surface temperatures of the plaster ceiling would be required.

4.5. Digital Energy Demand Simulation.

The results showed that the thermal upgrading of the walls that was undertaken led to a reduction in energy demand of 12%. It is interesting to note that, assuming secondary glazing would not only improve the thermal performance of the windows but also lead to increased airtightness, this alone could potentially achieve a reduction of 15%. The introduction of 200mm wood fibre insulation to the roof could potentially have achieved a 17% reduction alone, or 42% when combined with the walls, and 58% combined with walls and secondary glazing. This calls into question if the thermal upgrading of the walls was actually the most efficient retrofit action to undertake. However, given that this project was not envisioned primarily as an energy retrofit, any reduction in energy demand should be seen as an added benefit and must be weighed against the other complex decisions of traditional building conservation.

5. Conclusions

The incidental thermal performance improvements achieved by the necessary replacement of failed 20th century panel infill materials have shown to be successful at the level of the building component, with U-values of the new panels achieving Building Regulations, however at a building scale the

positive impact on energy demand reduction (12%) and hygrothermal comfort levels is limited (achieved only an average of 53% of occupied hours). At the same time there exists the possibility that the work undertaken may have a negative impact through the concentration of condensation on the 17th century plastered ceiling. In order to verify if condensation is occurring, further detailed monitoring of surface temperatures and hygrothermal conditions is required. The results presented here underline the need for wherever possible a holistic approach to energy retrofit, however this must be balanced by the complexities of sustainable building conservation.

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