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In-situ monitoring of thermal refurbishment on pre-1919 properties in Scotland

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This work describes the use of in-situ monitoring techniques to establish the building performance of pre-1919 traditionally constructed buildings and evaluate different thermal refurbishment strategies using component U-values as a recognised indicator of building envelope performance. The buildings monitored were of traditional construction (solid wall), some of which were listed or in a conservation area, constructed from lime-bonded rubble or ashlar, typically circa 500 mm thick, with natural slate or tile roofs, timber doors and single glazed windows. In-situ pre-intervention U-values were obtained after monitoring each building component constituting the existing building envelope and again at post-intervention; where insulation materials were added at varying interfaces. Using the improvement data two case studies were modelled using the UK Standard Assessment Procedure (SAP) software; showing that significantly reduced levels of building heat loss and carbon dioxide emission were achieved after thermal rehabilitation.

Introduction – context & background

This paper sets out the pre and post-intervention monitoring work carried out by the SEC at Edinburgh Napier University in collaboration with Historic Scotland Conservation Directorate as part of the energy efficiency refurbishment pilot scheme for traditional buildings. The research starts by measuring the actual thermal transmittance of building components followed by quantifying the thermal improvements achieved by selected upgrade measures.

The research originates as the topic of refurbishing or retrofitting the existing housing stock in Scotland is a concern to the Scottish Government, hence the involvement of Historic Scotland who have the responsibility of safeguarding Scotland's historic environment. The priority is to reduce energy demand and carbon dioxide (CO_2) emissions, currently attracting much attention in the UK (Jones, 2013). Although the focus of the current research is based in Scotland, the results are applicable to the UK and other EU countries where large numbers of a similar archetypes exist and retrofit is of interest. Traditional and historic housing have shaped the urban landscape for centuries, therefore evaluating the thermal performance of these buildings is a priority in meeting global targets.

Current scenario - the housing stock & energy use/ CO_2

Currently the UK housing stock comprises of more than 27.3 million dwellings of different archetypes and ages; with differing thermal performance. It is estimated that 5.8 million dwellings in the UK were constructed before 1919, as shown in Figure 1a, this is 22% of the UK housing stock (Palmer, 2012). Scotland has 2.37 million households; 459,000 of which are pre-1919 construction, typically considered to be poor energy-performing houses unable to provide required internal thermal comfort for occupants. In the UK fewer than 180,000 new homes are built each year (Palmer 2012), balanced against a small percentage of homes which are demolished or upgraded; resulting in an impoverishing housing stock that is thermally poor (Palmer, 2012).

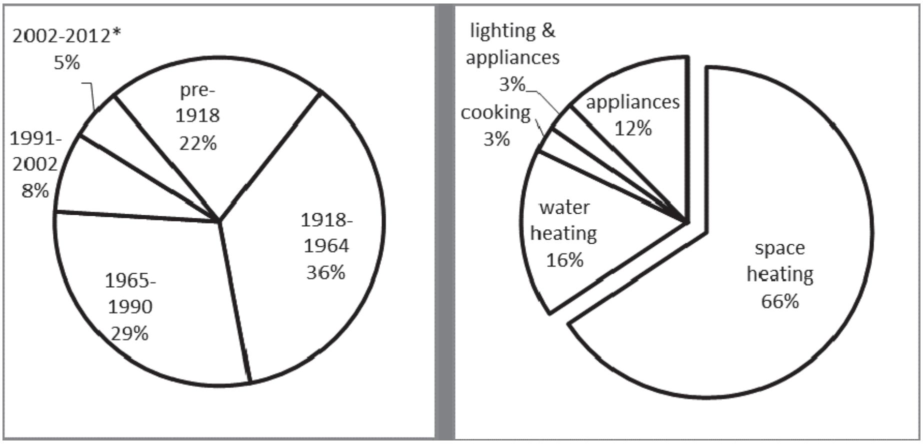

Figure 1. a. Age distribution of UK housing stock (Palmer, 2012); b. Percentage breakdown of typical household energy consumption (DECC, 2013).

Conventionally the energy performance of houses is embedded during design and construction stage. Opportunities for enhancing energy efficiency only arise during infrequent refurbishment activities. Traditional solid wall buildings typically have a wall thickness of over 500mm and are perceived as thermally poor with high fabric and ventilation heat loss, especially during the heating seasons. This is due to a thermally inefficient envelope, with high U-values and low air-tightness, or poor permeability.

Around 50% of the UK's energy use and carbon dioxide emissions are associated with buildings, of which 28% is attributed to housing (DECC, 2013). Figure 1b, shows the percentage breakdown of energy use in the UK domestic setting. 66% of all household energy use is related to space heating (DECC, 2013), this is a significant amount therefore warrants an effective strategy to reduce fabric and ventilation heat loss through the building envelope (Palmer, 2012). Recent surveys and studies have shown that 7.8% of pre-1919 dwellings are failing to meet tolerable standards; accounting for 49% of the dwellings that fail thermal performance criteria set by the Housing (Scotland) Act 2006 (Scottish Parliament, 2006). Nationally published statistics in the recent Scottish House Condition Survey, (Scottish Government, 2011) show that pre-1919 dwelling types contribute more to domestic CO_2 emissions than any other house age.

Historic building architecture

The properties featured in this paper are typical examples of construction types in Scotland dating before 1919. All of the properties are of traditional construction (solid wall), and some are catalogued for their preservation (listed). Most are constructed from lime-bonded stone rubble or with both rubble and an ashlar frontage. Wall elements are typically 400 to 600 mm thick, with natural slate or tile roofs, and timber floors, windows, and doors. The properties in this research paper have been selected from eight sites which represent a range of building types from across Scotland.

Methodology

This paper describes a study assessing in-situ measured U-values from a range of traditional building elements and components: walls, floors, ceilings and windows. This paper presents the results of a range of thermal enhancements applied to two selected dwellings.

Principles for investigating thermal transmittance

Measuring the thermal transmittance, or U-value, through elements of traditionally constructed buildings provides an insight to the thermal performance of the envelope of that building. The U value, of a building element or component is defined in BS EN ISO 7345:1996 as the "heat flow rate in the steady state divided by the area and the temperature difference between the surroundings on each side of a system". Its units are defined as watts per meter squared degree Kelvin (W/m^2K).

The testing methodology for calculating the in situ U value measurements has been applied by Baker (2008), Baker (2011) and Rye (2011). ISO/DIS 9869-1:1994 was followed to conduct In-situ U-value measurements presented and discussed in this paper.

The methods set out in BE EN ISO 6946:2007 for the calculation of steady state U-values were used, in conjunction with BE EN ISO 10456: 2007 to derive the thermal conductivity values for each material. These calculations were performed to validate the in-situ measurements.

To obtain a baseline figure, pre-intervention in-situ U-value measurements were obtained of the building component, following that the properties underwent thermal upgrading (retrofitting) in the form of insulation being added to various elements. Concluded the retrofitting, the U-values were re-measured, thus comparing the pre and post-intervention U-value and quantify the improvements.

Sensor type

The in-situ U-value measurements were taken using Hukseflux HFP01 thermopile-based heat flux transducers (Fig. 2) of 80 mm diameter and 5mm thickness. The expected typical accuracy averages ±5%. These were attached internally to each building element being tested throughout the period of monitoring, typically above 14 days as described by Baker (2011). Where possible, two of these devices were co-located in order to promote spatial averaging, and to provide protection against potential equipment failure.

The elemental U-values were determined by recording differential voltage from the heat flux transducers through the element together with internal surface and external air or surface temperature using calibrated K-type thermocouples (Accuracy: ±0.5°C) both connected to Grant Squirrel data loggers with 24bit A/D conversion resolution (Accuracy ±0.1°C).

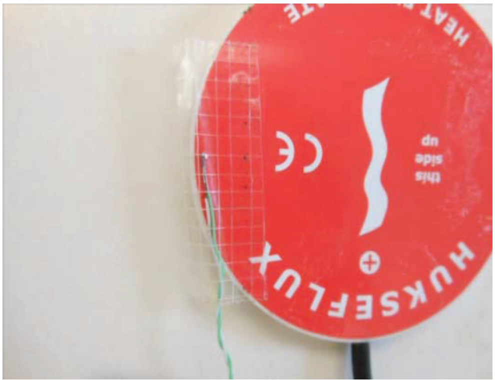

Figure 2. K-type thermocouple mounted to face of heat flux transducer, placed on test wall.

Where required, calibrated Tinytag temperature (Accuracy ±0.3°C) / humidity loggers (Accuracy ±3.0% RH at 25°C) were used for verification purposes and where thermocouples could not be affixed adequately.

Calculating the building energy performance

The Standard Assessment Procedure (SAP) is the UK's adopted software for complying with the European Directive 2010/31/EU for energy performance rating. It produces an energy performance certificate providing ratings for energy performance and environmental impact (CO_2). This is achieved through the calculation of space heating required ($kWh/m^2/year$) to maintain an internal temperature whilst balancing heat losses and heat gains. External temperatures are derived from one national weather file and internal temperatures accumulate the useful gains such as metabolic and solar gains, and heat losses from fabric and ventilation. For the normal SAP heating schedule, the heating season comprises 68 weekend days with 16 hours of heating and 170 weekdays with 9 hours of heating (2 hours in the morning and 7 hours in the evening). Summer months are included here only for consideration of cooling (BRE, 2011). The SAP scale of performance ranges from 0 to 100; higher score depicts higher energy efficiency and less environmental impact (CO_2) which is then supported by a band of performance and impact from A (highest) to F (lowest).

SAP methodology is criticised for its single centralised weather file used for every dwelling in the UK (Ingram & Jenkins 2013). There are also doubts on how accurate SAP models are for assessing historic and traditional buildings (Kelly et al., 2012). Results are considered inaccurate with predictions often underestimating thermal performance of the existing fabrics and overestimating potential savings after refurbishment (English Heritage, 2007).

Case Study 1: Wells O' Wearie

Wells O' Wearie cottage is a small single storey detached building dating from the early 19th century, with an east - west orientation. The cottage is constructed of sandstone rubble, bound with lime, and finished with ashlar quoins and margins. The property is owned and managed by Historic Scotland (Curtis & Jenkins, 2012). It is located in Holyrood Park area of Edinburgh (Scotland) on a sheltered site below the road level (Fig. 3). Pre-intervention monitoring took place during October 2010 whilst the property was unoccupied.

Heat flow mats were positioned to monitor heat transfer through the walls, floor, ceiling and window glass. Four heat flow mats were attached to three walls during the pre- and post-intervention stages. Two heat flow mats were added to the north wall on either side of the window, a single mat was added to the west wall and one to the east wall, all attached to the internal surface of the wall. A heat flow mat was also added to the centre of the window (Fig. 4). Data was logged at two minute intervals over a period of three weeks. The average outdoor temperature recorded was 8°C with a relative humidity of 75%. Internally the average temperature was 15°C at 49% relative humidity. Post-intervention monitoring took place between February and March 2012 during a three week period. The heat flow mats were reinstated on the same locations as the pre-intervention period; average readings showed: internal temperature of 18°C at 60% relative humidity and external temperatures of 9°C and 80% relative humidity.

Figure 3. Wells O' Wearie facing north west.

Figure 4. Heat flow mats on north east wall & window.

Thermal enhancement strategy and results

Two approaches were taken to improve the thermal performance of the walls. Shredded cellulose material was blown in the 30 mm void between the lath and plaster finish and the face of the sandstone wall lining on the north and east-facing walls, creating an insulated layer between the timber studs, (Fig. 5a); while an aerogel lining was applied to the internal surface of the west wall (Fig. 5b). These interventions are applied when internal timber finishes, cornicing and window details must be retained, or where it would be difficult to apply material to the face of the lining. The north (2 heat flow mats) and east (one heat flow mat) facing walls U-value improved from 1.3 W/m²K measured pre-intervention, to 0.6, 0.8 and 1.0 W/m²K respectively for the three different test points at post-intervention – both walls had lose cellulose in its cavity.

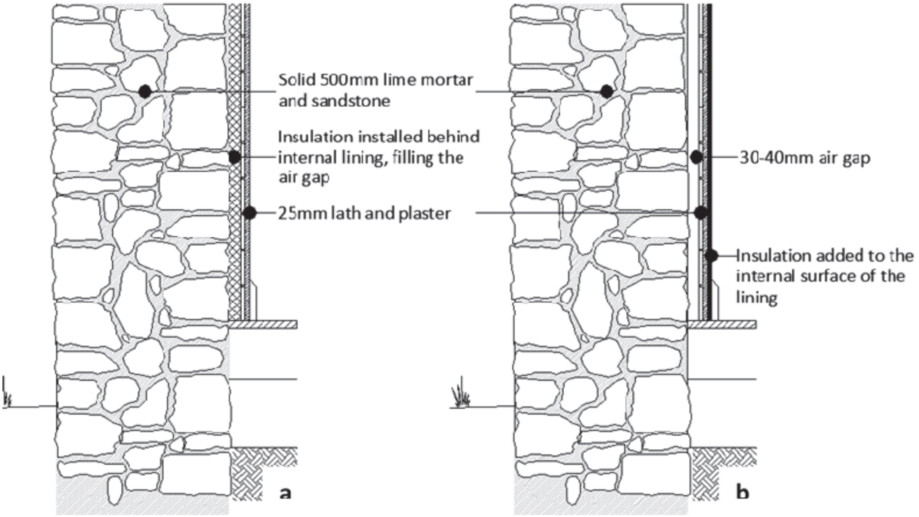

Figure 5. Construction details showing application of insulated to wall at Wells O' Wearie, a. insulated blown into cavity, b. Insulation applied to internal lining.

The 10mm aerogel lining was attached to the internal surface of the lath and plaster and affixed with a mesh liner then fastened with thermally decoupled fixings. To allow proper coverage of the wall, the skirting boards and decorative facings were removed and two coats of renovating plaster were then applied to finish, skirting boards etc. were then reinstalled. The U-value changed from 1.4 W/m²K with no insulation to 0.7 W/m²K with the aerogel addition. The addition of 280mm sheep's wool insulation placed above the lath and plaster ceiling, laid between and above the ceiling joists, improved the U value from a nominal 1.4 W/m^{2}K to 0.2 W/m^{2}K. The suspended timber floor also showed an improvement; from an original U value of 2.4 W/m^{2}K, which, after wood-fibre insulation batts were installed underneath the floorboards, fixed with battens, dropped to 0.7 W/m^{2}K.

Secondary glazing with a magnetic tape securing a proprietary single sheet of transparent polycarbonate was affixed to the inset of the window frame reducing the thermal transmittance from 5.4 W/m^{2}K to a value of 2.4 W/m^{2}K, which is comparable to the U value delivered by a double-glazed window unit. This glazing arrangement allowed the shutters to continue to function, adding further reduction in thermal heat losses and air leakage.

Case Study 2: Wee Causeway: Culross: Fife

The building is a detached cottage referred to as 'Wee Causeway' (Fig. 6), located in the village of Culross, Fife, cared for by the National Trust for Scotland.

The original fabric dates from the mid-18th century. It consists of a sandstone rubble masonry wall bound with lime, although has been re-pointed with cement in several areas. Internally the walls in the ground floor rooms are lined with lath and plaster, others have plaster 'on the hard' (i.e. directly onto the masonry). All rooms had a standard cornice detail in place (Curtis & Jenkins, 2013). It has a pitched pan-tile roof common to the east coast of Scotland and the windows are single glazed sash and case.

Figure 6. Front elevation of Wee Causeway Cottage.

Figure 7. Heat flow mats on ground floor walls.

Pre- and post-intervention in-situ U-value measurements were taken from five elements across two rooms in the cottage. On the ground floor, heat flow mats were fixed to the surfaces of the West and South facing walls (Fig. 7). On the first floor the heat flow mats were fixed to the West and North wall and the ceiling.

The pre-intervention monitoring took place at the end of November 2010 whilst the property was occupied. The monitoring lasted 15 days during which time the internal temperature averaged 13°C and the relative humidity 53%. The outdoor temperature averaged 5°C, with temperatures dropping to 0°C during the night and late evenings. The external average relative humidity was 76%. At post-intervention, data logging equipment was installed for 15 days during February 2012; the same elements were tested providing consistency in the findings. During this occupied time, internal temperatures averaged 15°C, with peaks reaching 23°C with an average relative humidity of 55%.The average external temperature was 10°C, with night time temperatures reaching 3°C with an average relative humidity of 73%.

Thermal enhancement strategy and results

Pre-intervention monitored walls recorded similar U-value results, 1.3 W/m²K and 1.5 W/m²K for the uninsulated walls with lath and plaster lining and 1.2 W/m²K and 1.6 W/m²K for the uninsulated walls with plaster on-the-hard. These values fall within the U-value range previously reported by Baker (2011) & Rye (2010) for similar construction elements.

Ground floor and first floor walls were insulated in different ways. Ground floor walls were insulated with polystyrene beads blown into the cavity between the stone wall and lath and plaster lining. The U value decreased to 0.5 W/m^{2}K at both measurement points.

The first floor walls received 10mm of aerogel blanket secured directly to the internal surface of the plaster on the stonework. Again the addition of the insulation harmonised the U-value result, both heat flow meters returned a U-value of 0.9 W/m^{2}K, showing an improvement of 0.3 and 0.7 W/m^{2}K respectively against pre-intervention results. Hemp wool insulation was added above the ceiling laid between and on top of the timber ceiling joists, as a result the U value improved from 1.2 to 0.2 W/m^{2}K.

Whole room heat loss

To contextualise the thermal step change achieved in each dwelling, SAP modelling software was used to generate space heating requirements, energy efficiency and carbon dioxide ratings. This was only carried out for the trial rooms and does not necessarily represent the other rooms in each dwelling or the building as whole.

Wells O' Wearie was modelled using the U-values discussed in Section 3.1, the nominated heating system was electric portable room heaters. The SAP results show a pre-intervention heat loss/ space heating requirement, for that one room at 489 kWh/m²/year. Using predicted EU energy performance certification, at pre-intervention the energy efficiency rating was G11 with an environmental impact CO_2 of F23. Post-intervention heat loss calculations found that space heating requirements for that room reduces to 266 kWh/m²/year, the energy efficiency rating improves to F35 and an environmental rating improves to E42. A further improvement reached 199 kWh/m²/year E45 energy efficiency rating and E50 environmental rating when including the chimney balloon in the flue to restrict air movement in winter.

Wee Causeway property was modelled using the U-values discussed in Section 3.2 with a nominated gas boiler heating system with room radiators as heating emitter. The results show a pre-intervention heat loss/ space heating requirement of 251 kWh/m²/year for the two rooms, E53 energy efficiency rating and E53 environmental impact CO_2 rating. At post-intervention the heat loss/ space heating requirement reduces to 167 kWh/m²/year total for the two rooms, the energy efficiency and environmental rating improves to D62 and D64 respectively.

Conclusion

This paper has discussed the results obtained from in-situ U-value monitoring of two dwellings of similar archetypes and thermal problems. They both presented thermal envelope deficiencies with high energy demand profiles in order to reach adequate thermal comfort. The study has highlighted how after thermal upgrades, the U-values decrease considerably while also reducing the environmental impact and energy demand. It has highlighted how with the use of Heat Flow apparatus under the ISO/DIS 9869-1:1994 methodology, measurements of pre and post-intervention can demonstrate the thermal benefits of such upgrades to the dwellings envelope.

The case studies demonstrated how various components were tested and monitored producing substantial reductions in thermal transmittance. For example, it was observed that in the Wells O' Wearie dwelling, the two walls monitored at pre-intervention had an average improvement of 30% in U-value at post-intervention. The same applies to the third wall where pre-intervention and post-intervention improvements reached 50%. Other components showed similar improvements; Ceiling, 70% and floor, 85%. In relation to Windows, the single sheet of polycarbonate used in the north east window, is effectively behaving as a fully-removable secondary glazing unit, reaching a reduction of 55% in U-value.

The Wee Causeway property tested two rooms. Ground floor walls were treated with polyurethane beads blown into their cavities presenting a decrease in thermal transmission of 65%. Equally first floor interventions with an aerogel blanket on the internal face of the walls showed improvements of 25% and 44% respectively. The ceiling in first floor also saw improvements of 85% where Hemp insulation was laid in-between and on top of the ceiling joists. These improvements were also evident through the SAP calculations of each room where space heating requirements reduced substantially as well as its impact on the environment with the reduction of CO_2 pollutants into the atmosphere. Wells O' Wearie presented 50% reductions while Wee Causeway 34% improvement.

In order to ensure that historical buildings are preserved and are energy efficient and economically viable, it is important to carefully consider methods and materials which will be sympathetic and understanding to the buildings original fabric and characteristics. It has become part of the culture within architectural technology to pursue low U-values, however this is not the only means by which to assess a successful retrofit programme. Reducing CO_2 emissions through lower space heating demand has immediate results for occupant's fuel bills. Equally important is the knowledgeable selection of insulating materials, associated hygrothermal properties, and behaviour into existing building fabric.

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Acknowledgements & further reading

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