High- and low-impact strategies for the internal insulation retrofit of traditional masonry walls

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ABSTRACT

This paper discusses options for internally retrofitting traditional solid masonry walls with insulation, categorising them into two different retrofit strategies: high-impact retrofit and low-impact retrofit. Both strategies are illustrated with refurbishment case studies from the United Kingdom. All buildings described in the case studies are historic buildings, constructed before 1910 with solid masonry walls.

The high-impact retrofit strategy aims at achieving significant thermal improvements. Such improvements are costly, impact on building fabric and building spaces and cause disruption to building occupants. They can also negatively impact on the heritage significance of the affected building fabric and spaces. Low-impact retrofit, by contrast, aims at achieving lower thermal improvements with a lesser impact on fabric, spaces, heritage significance and occupant disruption.

Both retrofit strategies are firstly described, secondly illustrated with case studies and thirdly discussed by comparing them, placing them into a governmental policy context and considering moisture-related risks.

Keywords

Building conservation; building refurbishment; EFFESUS; energy efficiency; historic buildings; insulation retrofit; internal wall insulation; solid masonry walls; traditional buildings; United Kingdom

1. Introduction

Improving the energy efficiency of existing buildings is essential to achieve the set reduction targets for greenhouse gas emissions. This will have to include improvements to historic buildings. Such buildings do not necessarily have to be protected as designated heritage (e.g. as 'listed buildings'). In the United Kingdom (UK), many of the existing historic buildings were erected before the early 20th century with external walls which are distinct from those of later buildings, in that they allow moisture transport within the wall fabric, without any particular layer in the construction stopping this transport. Examples for such constructions are solid masonry walls, made with brick or natural stone, bedded in lime mortar. Such walls are also referred to as 'traditional walls'.

Improving the thermal performance of external walls is considered to be an important measure to achieve reductions of energy use and carbon dioxide (CO_2) emissions. For 20th century buildings, such improvements are commonly done by retrospectively filling the cavity existing within the masonry of most walls of this period; these walls are therefore referred to as 'cavity walls'. In traditional masonry walls though, no cavity exists within the masonry, leaving external or internal wall insulation as the only retrofit options. Externally applied insulation is generally considered inappropriate for historic buildings, as it significantly changes a building's exterior appearance. In historic buildings, internal wall insulation is therefore often the only option to considerably improve the thermal performance of traditional walls.

Traditional walls in Scotland, but also in other parts of the UK, are often finished internally with 'plaster on laths', i.e. plaster applied to timber laths which are nailed to timber battens fixed to the walls. This leaves between the battens air-filled voids of a depth of 20 to 50 mm. These voids between wall finishes and masonry surface are obviously cavities, but is often referred to as 'air space' to distinguish them from the cavities in cavity walls, where the cavities are located within the masonry (and insulation is generally injected from the exterior).

This paper discusses options for internally retrofitting solid masonry walls, categorising them into two different retrofit strategies: high-impact retrofit and low-impact retrofit. The paper describes –as high-impact retrofit– conventional, surface-applied retrofit solutions, as commonly used in the UK today, and –as low-impact retrofit– injected insulating solutions, suitable for retrospectively filling the air spaces behind internal wall finishes, such as plaster on laths (but also plasterboard on dry-lining).

The high-impact retrofit strategy aims at achieving significant thermal improvements. Such improvements are generally costly, impact on the building fabric and building spaces and cause disruption to building occupants during installation. They can also impact negatively on the heritage significance of the affected building fabric and spaces. Low-impact retrofit, by contrast, aims at achieving lower thermal improvements with a lesser impact on building fabric, and spaces, their heritage significance and disruption to building occupants.

Both retrofit strategies are illustrated in this paper with refurbishment case studies from the UK. All buildings described in the case studies are historic buildings, constructed before 1910 with traditional masonry walls. One case study is a

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high-impact retrofit in London, designed by Anne Thorne Architects and funded through the Retrofit For The Future programme. The other case studies are low-impact retrofits in Edinburgh and Glasgow and have been carried out on behalf of and/or supported by Historic Scotland, an agency of the Scottish Government charged with safeguarding and promoting Scotland's historic environment. The paper also describes a proposed retrofit case study in Glasgow, planned as part of the European research project EFFESUS.

Both retrofit strategies –high- and low-impact retrofits– are firstly described, secondly illustrated with case studies (including financial costs and impacts on building fabric and spaces, heritage significance and occupant disruption) and thirdly discussed by comparing them, placing them into a governmental policy context and considering moisture-related risk.

2. High- and low-impact retrofit strategies

2.1 High-impact retrofit

Commonly, external walls are retrofitted internally by applying new insulating materials to the internal wall faces. These surfaces can either be retained wall finishes or masonry surface where existing wall finishes have been removed. The impact of such surface-applied internal wall insulation on building fabric and spaces, apart from achieving a thermal improvement of the wall, is that it

- reduces floor-space areas and changes the proportions of rooms, (which might not be immediately noticeable in larger rooms, but can have a significant visual impact in smaller rooms),
- often results in the loss of existing wall finishes, which can be of heritage significance, (although the retention of existing wall finishes behind the new insulation is sometimes possible),
- often results in complicated and problematic detailing at window and door openings,
- impacts on the appearances of rooms by covering visually important wall features, such as moulded architraves, cornices, dado rails, skirtings etc., (although such features can sometimes be reinstated),
- results in thermal bridging at junctions of building elements, e.g. where external walls meet floors and internal walls, (which also makes the installation of continuous air- and vapour-control layers difficult).

To what degree internal insulation improves the thermal performance of a wall depends on the insulating materials used and on the thickness to which these materials are installed. Generally, the thicker the insulation, the better it performs thermally – but the more it also impacts on the room's appearance. Some advanced insulating materials, such as aerogel, can achieve the same thermal performance as conventional insulating materials with only a fraction of the thickness of the conventional materials.

Which thickness insulation is installed in a building retrofit depends not only on the aimed-at thermal performance, but also on technical practicalities and financial costs. A retrofit which aims at achieving the highest, practically possible level of thermal performance requires insulation of a substantial thickness or thermally highly performing insulating materials or both. Such a retrofit can be called 'high-impact', with the term 'high-impact' not only referring to the thermal performance, but also to its impact on the room physically and visually. Because the high-impact retrofit is generally in the form of surface-applied insulation, it also causes considerable disruption to building occupants during installation.

2.2 Low-impact retrofit

Many traditional walls in Scotland and other parts of the UK are finished internally with plaster on laths and therefore contain air spaces behind these wall finishes. These existing cavities with a depth of 20 to 50 mm can retrospectively be filled with insulation, by injecting into these air spaces from the room-side insulating materials in the form of beads, fibres or foams. A layer of, say, 30 mm thick injected cellulose fibres does obviously not achieve the same thermal performance as a 100 mm thick cellulose-fibre board, but is nonetheless still an improvement.

Retrospectively filling an existing cavity has no impact on the visual appearance of a room. It also has only a minimal direct impact on the existing building fabric: holes need to be drilled to infill the insulating material into the cavity and need to be 'made good' after the installation is complete, which generally includes some redecoration. The installation can be done in a short space of time and with minimal disruption to the building's occupants, compared to surface-applied insulation retrofits. It should be considered best practice to carry out pre- and post-retrofit investigations, e.g. to check pre-retrofit the condition of the air spaces with borescopes and post-retrofit the achieved workmanship with thermal imaging cameras.

However, the existing air spaces not only contribute to the thermal performance of the wall, but can, depending on the situation and if vented, also influence moisture and salt transport (by acting as capillary breaks, allowing evaporation from the masonry and impacting on salt migration). Filling these air spaces with insulation will alter the wall's hygrothermal performance (see section 4.3).

In practice, many plaster-on-laths finishes have been replaced over the past decades with plasterboard on dry-lining, often with studwork thicker than the previously used battens. Unless done relatively recently, it is likely that no or only minimal quantities of insulation were installed during the replacement. As with plaster-on-laths finishes, the existing cavities behind the plasterboard can be retrospectively filled with injected insulation, and more insulation can often be infilled due to the thicker studwork and the thereby deeper air spaces.

The strategy of retrofitting wall insulation internally by filling existing cavities behind internal wall finishes can be called 'low-impact' retrofit. The term 'low-impact' describes not only the impact on the thermal performance but also the impact on the building fabric and spaces and their heritage significance. The disruption to the building's occupants is also minimised as existing wall finishes are retained in-situ, (requiring some re-decoration though).

3. Retrofit case studies

3.1 High-impact retrofit case study

A widely publicised retrofit project is the refurbishment of an early 20th century terraced house in London by Anne Thorne Architects, completed in 2011. [1] The project was funded by the Technology Strategy Board, a UK public body, through their Retrofit For The Future programme, to produce "exemplar retrofitted properties with radical and realistic solutions" [2]. The thus funded refurbishments were to "deliver deep cuts in energy use and carbon emissions" [3].

The building is an Edwardian (1901-1910), mid-terrace house in London's Haringey district. The building has two storeys and three bedrooms. Its external walls are 220 mm thick brick masonry, unrendered externally and 'plastered on the hard' internally (i.e. no air spaces). The retrofit aimed at "an 80% reduction [in CO_2 emissions] on UK average housing" and has been "designed to passivhaus standard" [4]. The refurbishment encompassed a variety of improvement measures, including heat recovery ventilation, solar hot water and window replacements.

The improvement measure of interest for this paper is the retrofit of wall insulation. Both external walls –the street-facing front elevation and the garden-facing rear elevation– were retrofitted. Because of the building's location within a conservation area, the use of exterior wall insulation to the ornately decorated front façade was deemed not acceptable by the planning authorities, leaving internal wall insulation as the only retrofit option for this wall. The rear wall was insulated externally. (Figure1)

The front wall was retrofitted internally with 260 mm insulation, consisting of two layers of 100 mm thick sheep-wool insulation batts and 60 mm thick wood-fibre board insulation, achieving a U-value of 0.21 W/(m²·K) for the wall. (Figure 2) The rear wall, insulated externally with 240 mm thick expanded polystyrene (EPS) boards with a render finish, achieved a U-value of 0.15 W/(m²·K). [5] For comparison, solid brick walls of a thickness of approx. 220 mm, achieve a U-value of approx. 2.1 W/(m²·K). [6] To reduce thermal bridging where the upper floor meets the external walls, perimeter floorboards were lifted and insulation added between the joists. This type of internal insulation retrofit meant that floor areas of rooms were reduced considerably, room proportions altered and original wall finishes covered up. The building was unoccupied during the period of refurbishment works, and occupation would have been practicall impossible during the works.

Figure 1 External wall insulation was only acceptable for use on the rear elevation of this mid-terrace house Copyright © Anne Thorne Architects.

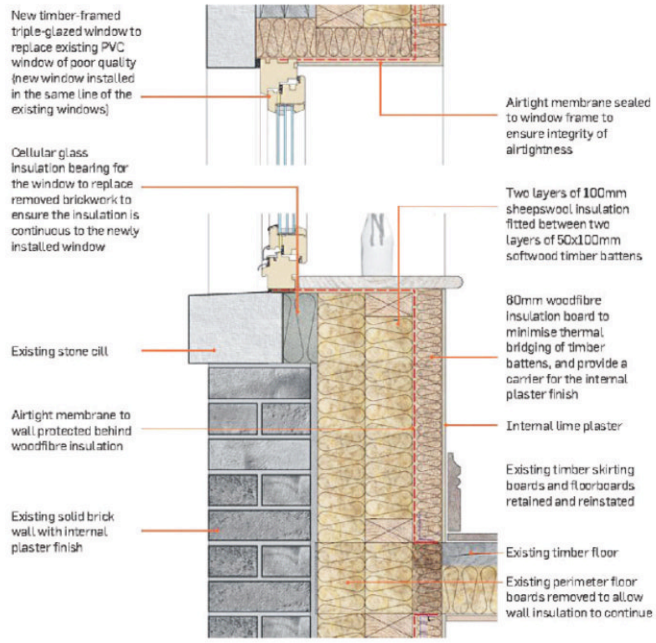

Figure 2 Brick wall retrofitted internally with 2 x 100 mm sheep-wool and 60 mm wood-fibre insulation Copyright © Anne Thorne Architects.

The cost for the complete refurbishment –not just the retrofit of the external walls– was £150,000, "of which £89,000 covered retrofit building works which have [allegedly] delivered deep cuts in energy use and carbon emissions" [7]. However, no measured data have been published, to date, to quantify this statement. A monitoring programme of the retrofitted building, conducted a team from University College London, which statrted in 2011 and is expected to be completed in 2013. [8]

The above case study suggests that significant reductions in energy use and CO_2 emissions can be made through building retrofit. However, it also illustrates that achieving such reductions requires substantial capital investment and is hardly possible without causing the decanting of or severe disruption to the building's occupants. These are both factors which are likely to deter building owners from carrying out such energy-efficiency retrofit measures.

This case study is a good example to illustrate the high-impact retrofit strategy, which certainly has its applicability in some refurbishment situations.

3.2 Low-impact retrofit case studies

The alternative to high-impact retrofit, as illustrated in the case study above, is a retrofit which does not seek to improve walls thermally to outstandingly high levels, but is satisfied with achieving somewhat lower levels of thermal improvements – and achieving these at significantly lower costs and with far less disruption to occupants and building fabric and spaces, particularly where the latter two are of heritage significance. This low-impact retrofit strategy has been used over the past years in a series of case studies in Scotland, carried out on behalf of and/or supported by Historic Scotland. "The refurbishments typically incorporate experimental, adapted or non-standard materials, and novel upgrade measures." [9]

In this paper, three of these case-study projects are introduced, two of which included several properties: a variety of flats in tenemental buildings in Edinburgh and Glasgow and in a cottage in Edinburgh. In all of these projects, insulation was injected into existing air spaces behind internal wall finishes –either in the form of plasterboard on dry-lining or plaster on laths. Also described below is a planned case study in Glasgow, coordinated by Historic Scotland as part of the European research project EFFESUS. In this case study, adapted aerogel insulation was trialled for use as injected insulation.

3.2.1 Tenements at Sword Street, Glasgow

In 2010, the external walls of five flats in a tenement at Sword Street in Glasgow's Dennistoun district were retrofitted with insulation internally. [10] The flats, owned by a housing association, were unoccupied during the works.

The external walls of the building were solid sandstone walls and approx. 600 mm thick overall. The existing internal wall finishes were plasterboard on dry-lining, with studwork approx. 100 mm deep with no insulation, all installed during a previous refurbishment in the 1970s. These plasterboard finishes were considered to be of no heritage significance and, being somewhat in disrepair, were replaced with new wall finishes.

Each flat was retrofitted with a different insulation product, including insulating boards and injected insulation. The following insulating boards were installed, replacing the existing plasterboard: aerogel boards, hemp-fibre boards and wood-fibre boards. 'Loose' cellulose fibres were spray-applied in one flat, whilst the existing plasterboards had been removed for replacement. Only in one of the flats was insulation injected into the air spaces behind the internal, albeit now new wall finishes: the material used was EPS beads. (Figure3)

Of the materials used in these retrofits, only the cellulose fibres and the EPS beads were 'loose' (i.e. not-bonded) materials. Whereas the EPS beads were injected into the air spaces behind the plasterboard, the cellulose fibres were sprayed onto the wall faces, lined out with timber battens to received plasterboard as wall finish. (EPS beads, although 'loose' prior to application, bond together after installation; cellulose fibres remain unbound.)

Figure 3 EPS beads were injected into the air spaces behind plasterboard in a Glasgow tenement building Copyright © Crown Copyright (Historic Scotland)

The thermal performance of the walls was measured by Glasgow Caledonian University (GCU) before and after the retrofit, using in situ U-value measurements. [11] For the purpose of this paper, only generic λ-values, i.e. values for thermal conductivity, are listed in Table 1 below to allow comparison between the different insulating materials used and stone wool, as an example of an insulting material used in mainstream construction.

The comparison shows that aerogel insulation has the potential to achieve significantly higher thermal improvements. This is of particular benefit in locations where space for the installation of insulation is limited.

It was unfortunate that, due to the 1970s refurbishment of this tenement building, no original plaster-on-laths finishes had survived, as this would have been the initial aim of this refurbishment project.

Fortunately, the opportunity to trial and monitor insulation retrofitted behind plaster-on-laths finishes arose in 2010 in tenemental buildings in Edinburgh.

Table 1 λ-values of some insulating materials used in the Sword Street case study [12]

Insulating material	λ-value (ranges) [W/(m·K)]
Aerogel	0.013-0.014
Cellulose fibre	0.035-0.046
EPS	0.030-0.045
Hemp fibre	0.039
Wood fibre	0.039-0.061
For comparison:	
Stone wool	0.034-0.040

3.2.2 Tenements in the Old Town of Edinburgh

During the winter 2010/11, five tenemental flats in the Old Town conservation area of Edinburgh were retrofitted by Adam Dudley Architects to achieve energy efficiency improvements. "The aim of the project was to trial a series of site-specific interventions to establish the feasibility of undertaking thermal improvements to pre-1919 tenements without the tenants having to move out" [13].

As part of this project, several traditional stone walls were retrofitted by retrospectively filling the air spaces behind the existing plaster-on-laths finishes with EPS beads. The thermal performance of the exterior walls was measured in situ before and after the retrofit. [14]High- and low-impact strategies for the internal insulation retrofit of traditional masonry walls 2 below lists the construction details of the walls, the U-values measured in situ, the U-value improvements as percentages, the costs per area and the size of the areas insulated. For comparison, also tabled are installation costs for insulation based on data from the Building Cost Information Service (BCIS) of the Royal Institution of Chartered Surveyors. [15]

The results inHigh- and low-impact strategies for the internal insulation retrofit of traditional masonry walls 2 show that filling internal cavities of a depth of 30 to 50 mm with conventional EPS beads can improve the U-value of the wall by up to 50%.

The costs stated in the table include the "installation of insulation, main contractor's attendance, patching of blow holes" [16]. The stated costs do not include protection and re-decoration. "The costs are … based on relatively small quantities, in terms of the number of properties and rooms treated, and it is anticipated that an increase in the scope of works would results in a commensurate reduction in costs." [17]

The comparison of the costs in High- and low-impact strategies for the internal insulation retrofit of traditional masonry walls2 shows that insulating smaller areas costs significantly more than treating larger areas, with the costs for the case study lying at 40 to 50 £/m^2, compared to 6 to 7 £/m^2 at general commercial rates. However, even the more costly insulation retrofit of smaller areas is relatively cost-effective when compared to the commercial rates for replacing existing wall finishes with new insulated plaster on new dry-lining.

This case study demonstrates that low-impact retrofits can achieve meaningful thermal improvements at reasonable capital costs, whilst retaining existing wall finishes and minimising disruption to building occupants.

Although only the retrofit with EPS beads was trialled in the Edinburgh tenements, such beads are by no means the only insulating material which can be used to retrospectively fill the air spaces behind internal wall finishes. Other materials include cellulose fibres, stone-wool fibres, glass-wool fibres, sheep-wool fibres etc. Table 1 above shows that of the materials used in the Glasgow case study aerogel had the best insulating properties. To establish if aerogel, in the form of beads, can be used as insulation injected into cavities, a trial was carried out as part of a cottage refurbishment.

3.2.3 Wells O'Wearie, Edinburgh

Wells O'Wearie is a 19th century cottage in Holyrood Park in Edinburgh. The building underwent an energy-efficiency refurbishment in 2011. [18] As part of the retrofit, it was trialled if aerogel beads can be used as injected insulation to retrospectively fill the air spaces behind existing plaster-on-laths finishes. (Figure 4)

Figure 4 Insulating materials were injected into the air spaces behind plaster-on-laths finishes Copyright © Crown Copyright (Historic Scotland).

Aerogel is delivered in bead form to insulation manufacturers to process it further, e.g. by bonding it to mesh fabric, thereby producing an aerogel-containing blanket, which is then normally bonded to boards for easy use in the construction industry.

The bags of aerogel beads delivered to Wells O'Wearie contained already on delivery large quantities of aerogel dust, as some of the beads had broken down, presumably through vibrations during transport. Injecting the beads into the existing cavities proved difficult, as many beads turned into dust: "The pressures required for the blower were too high for the material, which, although in bead form, broke up in the hose and when in contact with the wall, producing a fine dust that proved difficult to control. The material was able to make its way into the solum and through very small gaps in the skirting boards". [20]

The aerogel trial at Wells O'Wearie demonstrated that aerogel beads are currently not stable enough for use as injected insulation. However, if aerogel could be developed into a more stable form, it could become a mixed high-low-impact retrofit: high-impact on thermal improvements, but low-impact otherwise. Developing aerogel further for use as injected insulation and trialling it in a case study is therefore part of the EFFESUS project.

Table 2 Results of internal-cavity insulation-fill, using polystyrene beads, and comparative costs

Location	**Thickness** [mm]		**U-value** [W/(m^2·K)]		**Improve.**	**Cost**	**Area**
	overall	cavity	Before retrofit	After retrofit	Percentage	[£/m^2]	[m^2]
Property A Living room	590 mm	30-40 mm	1.4	0.8	43%	50	4.75
Property C Bedroom	700 mm	35-45 mm	1.4	0.7	50%	40	12.2
Property D Living NW	630-650 mm	40-50 mm	1.3	0.7	46%	40	25
Below are "prices a developer might expect to pay on a medium-sized residential project for products in the low to medium specification range. Prices do not include for the contractor's preliminaries, overhead or profit margin. The base date is December 2011 at UK mean location and prices are based on BCIS Online Rates Database." [19]							
"50mm expanded polystyrene bead injected into cavity wall"						6.33-7.12	
"50mm insulated plasterboard … fixed … to softwood … slurry coat to surface"						85.02-95.65	

3.2.4 EFFESUS case study in Glasgow

EFFESUS is a research project, funded by the European Commission. The acronym stands for Energy Efficiency For EU [European Union] Historic Urban Districts' Sustainability. As its main output, "EFFESUS will produce … a software tool to help make informed decisions about improvement measures suitable for historic urban districts". [21] The project will also "develop and implement new or adapted technologies which are cost-effective and technically and visually suitable for use in historic buildings and urban districts." [22]

One of the technological developments supported by EFFESUS is the adaptation of aerogel for use as injected insulation behind existing internal wall finishes. The project partners responsible for the product development are A. Proctor Group, UK, and Active Space Technologies S.A., Portugal. Its performance and suitability will be tested in 2013/14 in field and laboratory trials by the project partner Fraunhofer Institute of Building Physics, Germany. Thereafter the new product will be trialled in a case study in a Glasgow tenement.

The EFFESUS case study in Glasgow is coordinated by Historic Scotland, also an EFFESUS project partner, in cooperation with Glasgow City Council. Both organisations have previously worked together on the retrofit of eight flats in Glasgow's Govan district. The in-situ monitoring of the properties was carried out by GCU. [23, 24] However, aerogel insulation was not used in these retrofits. The monitoring of one flat is still on-going due to an advanced monitoring regime, for which not only thermal performance (U-values) and vapour transport is being measured but also wind-driven rain. (Figure 5) These measurements try to establish if rain water can penetrate through such walls, reaching the internal wall faces. If this is the case, it can have a detrimental impact on internal retrofits long-term. Located near Scotland's west coast, Glasgow receives levels of wind-driven rain which are significantly higher and have a more severe impact than those at most locations elsewhere in Europe. [25] It is anticipated that the monitoring of the EFFESUS case study will be similar to that of the retrofit in Govan.

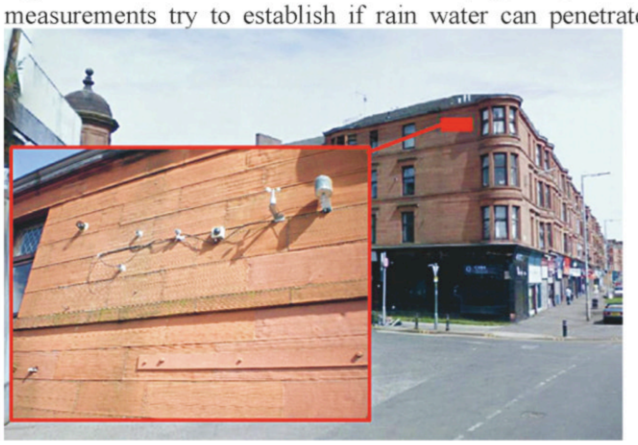

Figure 5 In-situ hygrothermal monitoring of a tenement building in Govan, Glasgow, including wind-driven rain measurements – Copyright © GCU

4. Discussion

In the sections above, two categories of retrofit strategies have been discussed: high- and low-impact retrofits. In this section, these strategies will be firstly evaluated and secondly placed into a governmental policy context; and lastly associated moisture-related risks will be considered.

4.1 Evaluating high- and low impact retrofits

The case studies described above have demonstrated that both retrofit strategies can achieve meaningful improvements in the thermal performance of traditional walls. As was to be expected, high-impact retrofits can achieve greater improvements than low-impact retrofits, but only at higher costs –financially, but also in terms of their impact on building fabric and spaces and on disruption to the building's occupants during installation. Such retrofits are therefore also likely to have a negative impact on the heritage significance of the affected fabric and spaces.

This paper has provided technical details of the wall insulation retrofits described above and has also provided (at least) some cost data for the retrofit works. It has become clear from the available cost data that comparisons are not easily possible. The Edinburgh tenement case studies have shown that the costs of experimental, small-scale retrofits do not reflect commercial market rates. For the London case study, overall costs were easily available, but more detailed cost data were not, making an analysis difficult. Without cost data readily available, it is not possible to easily compare the two retrofit strategies.

Evaluating the long-term feasibility of the retrofit strategies properly requires building-specific life-cycle analyses, placing the refurbishment works into context with a building's post-retrofit operational performance –both energy-wise and financially. Such life-cycle analyses are of particular importance for high-impact retrofits, as "embodied energy and carbon … is of increasing significance, the more energy-efficient buildings become in their use." [26] However, such assessments are rarely conducted for building retrofits. Unfortunately, embodied energy assessments and life-cycle analyses are not available for the case studies described above, again making comparisons difficult. The results of the monitoring of the London case study, if published, might provide useful data about both the hygrothermal performance of the building fabric and the energy use of the whole building.

4.2 Governmental policies context

To provide incentives for the energy-efficiency retrofit of the existing building stock, the UK government has introduced the Green Deal, a financial instrument allowing "householders to pay for energy efficiency improvements through savings on their energy bills" [27]. Recent research, analysing traditional buildings in Scotland, found that "significant subsidy is needed if traditional properties are to be retrofitted to make significant CO_2 and running cost savings. … In their current form, however it seems unlikely that the Green Deal and ECO [the associated, governmental subsidy programme] alone will provide sufficient subsidy to achieve this" [28]. Relating to retrofit of internal wall insulation, the research identifies as a particular barrier the clause that only improvement measures which achieve significant thermal improvements are eligible, i.e. high-impact retrofits. "Solid wall insulation is only eligible for ECO funding if it achieves a U-value of 0.3 [W/(m²·K)] or less" [29]. The research recommends that "relaxing the maximum U-value for solid wall insulation would allow more [insulation] systems to qualify for ECO, including the less disruptive and lower-cost options such as blown bead insulation." [30] The UK government's Green Deal and ECO appear, at the time of writing this paper, to only support high-impact retrofits of traditional stone walls; low-impact retrofit solutions appear not to be eligible.

4.3 Moisture-related risks associated with the internal insulation retrofit of solid walls

Retrofitting traditional walls with insulation internally improves their thermal performance, but also impacts on their moisture performance, as heat and moisture transport are intrinsically linked. Moisture is one of the main factors causing deterioration of building materials. Critically assessing this hygrothermal performance is therefore essential to prevent the long-term deterioration of building fabric and increase the longevity of retrofits, thereby making them truly sustainable.

Traditional walls are constructed using materials and techniques that allow the penetration of air and moisture, but constructed to a thickness substantial enough to generally prevent moisture from reaching the internal wall faces. Moisture can penetrate a traditional wall as liquid and vapour. Examples of liquid penetration are rain water (with wind-driven rain being of particular significance) and 'rising damp' (i.e. ground water rising in walls through transport by capillary forces). Water vapour is well known for its potential to cause interstitial and surface condensation, resulting in the deterioration of fabric and in mould growth, a health risk for building occupants. This paper cannot discuss in detail the impact of internal wall insulation on the hygrothermal performance of walls and the associated moisture-related risks, but provides below an outline of the issues to be considered.

High-impact retrofit, in the form of surface-applied insulation is generally fitted with a vapour-control layer to prevent indoor vapour condensing interstitially. However, this practice can potentially also impair the evaporation of excess moisture from interior wall faces. Low-impact retrofit is generally installed without a vapour-control layer. This can help improve indoor moisture evaporation, but depends significantly on the insulating material and the wall finishes present. Due to the lack of a vapour-control layer, it has often thought that interstitial condensation can occur (particularly where high levels of insulation have been retrofitted, thereby reducing the temperature of the masonry substantially). However, it appears that such concerns do not generally account for the ability of traditional masonry to absorb and disperse liquids.

Moisture transport in traditional wall construction is a complex phenomenon. Assessing the impact of internal wall insulation properly is, in practice, therefore difficult. This means that often an 'engineering approach', based on previous experience, has to be taken. Where traditional walls are not prone to liquid transport, e.g. in relatively dry, well ventilated locations, the retrofit with internal wall insulation appears unlikely to cause problems. However, in locations where liquid is likely to impact on a wall's performance, conducting an advanced hygrothermal assessment and choosing a risk-averse retrofit strategy appears prudent. Examples for such locations are areas where significant rising damp and/or wind-driven rain can be observed, such as at Scotland's west coast.

Further research is required to be able to make better informed decisions in practice about internal (but also external) wall insulation retrofit in locations where high levels of moisture transport can occur in traditional walls.

5. Conclusions

This paper has discussed options for internally retrofitting traditional masonry walls with insulation, categorising them into two different retrofit strategies: high- and low-impact retrofits. Both strategies were illustrated with case studies from the UK. High-impact retrofits can obviously achieve better thermal improvements than low-impact retrofits, but only at increased costs –financially and also in terms of their impact on building fabric and spaces and on disruption to the building's occupants during installation. Such retrofits are also likely to impact negatively on the heritage significance of the affected building fabric and spaces. The relatively high costs and significant disruption associated with high-impact retrofits is going to deter many building owners from carrying out such works.

Evaluating the feasibility of the two retrofit strategies requires building-specific life-cycle analyses. Such assessments are rarely conducted for building retrofits and were not available for the case studies described in this paper, thereby making comparisons difficult.

The UK government's Green Deal and ECO programmes appear, at the time of writing this paper, to only support high-impact retrofits of traditional stone walls; low-impact retrofits appear not to be eligible.

Retrofitting traditional walls with insulation internally improves their thermal performance, but also impacts on their moisture performance. Assessing the impact of internal wall insulation on the hygrothermal performance of such walls is, in practice, difficult. This means that often an 'engineering approach', based on experience, has to be taken. In locations where moisture appears likely to impact on a wall's performance, e.g. Scotland's west coast, conducting advanced hygrothermal assessments and choosing a risk-averse retrofit strategy appears prudent.

Low-impact retrofits can be of particular interest for buildings where the interiors are of heritage significance, because such retrofits have no impact on the visual appearance of building fabric and spaces and cause only minimal fabric disruption during installation. However, the long-term risks of moisture-related deterioration of the building fabric need to be properly assessed.

This paper has shown that various options are available to retrofit solid walls with insulation internally. However, to evaluate the long-term performance and thereby the feasibility of such retrofits requires more easily available data, including life-cycle analyses and advanced hygrothermal assessments. Further research is also required to better assess, in practice, the moisture transport occurring in traditional walls and its impact on insulation retrofits.

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