

Report to Joseph Rowntree Housing Trust

Project Title: Temple Avenue Project

Part 1: Temple Avenue field trial – Evaluation of design & construction process and measurement of fabric performance of new build dwellings

Part 2: Energy efficient renovation of an existing dwelling: Evaluation of design & construction and measurement of fabric performance

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Executive Summary

- 1 The Temple Avenue Project, funded by the Joseph Rowntree Housing Trust and conducted by the Centre for the Built Environment at Leeds Metropolitan University, outlines the initial evaluation of the design, construction and performance of two prototype low carbon dwellings and helps establish the extent to which an existing 1930s masonry house can be renovated so as to achieve a level of performance commensurate with the advanced energy and carbon standard of the prototype new dwellings. The two prototype dwellings contained some technological innovation and were constructed between July and December 2009. One prototype was constructed using thin-joint masonry construction and another using a structural insulated panel (SIPs) build system. The concurrent renovation works to an adjacent existing dwelling explored the impact of two standards of renovation, one reflecting the standard fabric measures that are currently considered to be cost effective and one reflecting the more challenging requirements of an 80% emissions reduction and incurring greater capital costs
- 2 Many of the issues raised in this report are due to the fact that the two new-build properties were prototype dwellings, and the refurbishment of the existing dwelling was performed as a prototype refurbishment. The Temple Avenue project was a learning process, and modifications to the designs as construction progressed were to be expected. This project covers only issues relating to the fabric performance of the dwellings and does not attempt to evaluate the full efficacy of the designs, builds and subsequent operation under occupancy with regard to CO₂ emissions.
- 3 Although significant successes were achieved in producing thermally efficient low carbon dwellings, particularly by UK standards, none of the final constructions fully achieved their designed levels of thermal performance. The separate Part 1 and Part 2 reports are more technical in nature and concentrate on these disparities, attempting to understand why and how they occurred and suggest how these differences in performance could be addressed under replication of the designs and measures adopted during this project.
- 4 Using a comparison of measured vs. predicted heat loss as an indication of the dwellings' fabric performance relies on the accuracy of both sets of data, this is not straightforward, particularly in the case of predicted values for existing dwellings. As the predicted heat loss relies on theoretical performances of materials installed ideally, it is highly unlikely that the predicted performance will be fully achieved in practice. With dwellings designed for low levels of heat loss, displaying the difference as a percentage of the predicted heat loss is unfavourable when compared to the percentage deviation of less thermally efficient dwellings. Even taking this into account, all three dwellings were amongst the best performing dwellings tested by Leeds Met in terms of measured vs. predicted fabric performance.
- 5 Whilst the measured heat loss coefficients obtained mimic those of the predicted values; it is suggested that the variations for phase 1 and 2 coheating tests on the existing dwelling are mainly due to inaccuracies in the predicted values, due to the number of assumptions of the original construction, variations for the phase 3 coheating test result on the existing dwelling and for the tests on the prototype dwelling were primarily due to the level of thermal performance not achieving that determined in the designs due to various factors outlined in the Part 1 and Part 2 project reports. The initial assessment of the existing dwelling was conducted in a manner which caused minimum disruption to the occupants, but as models and calculations require a higher degree of accuracy a more intrusive investigation would have been particularly beneficial in this instance.
- 6 The measured heat-loss coefficients provided effective mean fabric U-values of 0.44 W/m²K for the thin-joint prototype dwelling and 0.37 W/m²K for the SIPs prototype. The existing dwelling underwent reductions from an initial 0.99 W/m²K to 0.77 W/m²K for phase 2 and 0.47 W/m²K for phase 3. The phase 3 result compared slightly unfavourably to the mean U-values for the prototype dwellings of but is likely reduce further upon full completion of the renovation work on the existing dwelling.
- 7 The combination of both solar and ΔT effects prescribe the seasonality of the testing period, and should be the foremost criterion when planning any future coheating tests. Adjustments necessary for solar correction of 15.4 W/K and 12.3 W/K were recorded for coheating tests conducted in October and March. For the phase 3 test on the existing dwelling this represented a 9% increase over the raw measured heat-loss coefficient due to solar insolation, any coheating tests performed further outside the optimal winter period would inevitably require even larger solar adjustments which may start to overwhelm certain aspects being investigated. This would particularly be the case where the test dwelling was orientated to maximise solar gain.

- 8 Heat flux measurements on the prototype dwellings intimate that the designed U-values of a number of the building elements are minimum rather than average U-values for those respective elements and the effects of air movement at junctions and openings are far greater than predicted. Heat flux measurements in the existing dwelling showed that the combined effect of the cavity wall insulation (CWI) and external wall insulation (EWI) virtually eliminated the thermal bypassing identified in the internal cavity walls; even though significant reductions in heat loss from the external walls were measured the designed performance improvements were never fully achieved, with particular problems of variable fill densities associated with the retro-fill CWI of the brick-brick cavity walls.
- 9 Internal temperatures on the south facing facades of the prototype dwellings were observed to overshoot the 25 °C coheating test set point by up to 3K on days with prolonged unbroken sunshine, when external temperatures were still below 5 °C. This gives an indication of the likelihood that high internal temperatures in the Summer may be a problem in these dwellings.
- 10 Brief assessments of the design suggested that issues relating to process and sequencing could be more prominent in the design, particularly where construction needs to be performed "out-of-sequence" as far as the traditional sequence of trades and fixes is concerned. The designs and specification of membranes, tapes, filling materials, adhesives and sealants would have benefited from further clarification.
- 11 In the thin-joint prototype, considerable difficulties maintaining the integrity of the roof membrane around trussed rafters was not obvious from the sectional drawings. If both TS and LS section drawings were available this may have raised awareness of these difficulties at the design stage. With no primary air barrier specifically identified on the details for the SIPs prototype, confusion arose over where sealing of joints and penetrations was most appropriate; the addition of an air tightness membrane would add conceptual clarity as to what constituted the air barrier and where sealing should be performed.
- 12 The 2 stage renovation of the existing dwelling caused some additional complications to the design process. There was a lack of design information available to show how continuous air and thermal barriers would be achieved at the more complex details as part of both the stage 1 and stage 2 renovations. Such description of build process may not be expected in a project of this size and nature, but may require more regard if these processes are to be replicated. Additional costs were also incurred as a result of the 2 stage renovation process, preventing any simple cost benefit analysis of many of the individual measures introduced, but the 2 stage refurbishment allowed greater insight into the effectiveness of some of these discrete interventions. A full set of design details was not available for either stage of the existing dwelling renovations; however, it would be useful to produce detailed as-built drawings to allow for these evolved details to be used again, or adapted, for future renovations and refurbishments of similar dwelling types.
- 13 The designed existing building renovations appeared not to fully appreciate the full effects of potential thermal bridging and bypassing throughout the property. Full thermal simulation of the details would have been prohibitively expensive but whether the adopted y-values were appropriate for each respective stage of construction is uncertain and simulation of a small number of selected details would have proved useful; although thermal imaging surveys suggested that the EWI was extremely effective in substantially reducing many of the thermal bridging problems relating to the external walls. Specific edge sealing of the cavities, to reduce the likelihood and severity of many potential bypasses was not always possible, and where possible was not prioritised.
- 14 The involvement of the Leeds Met research team affected the project programming, with the schedule needing to be adapted to fit all the coheating tests into one heating season and performing all renovation work on the existing dwelling between test periods. This presented some difficulties for the refurbishment of the existing dwelling and was worked around by the project manager and site team, with temporary fixes and break-ins kept to a minimum. Regular contact was maintained between all concerned parties, particularly during some of the more critical stages of construction. This can be regarded as one of the successes of the project; it is difficult to see how some of the issues would have been resolved without such effective communication.
- 15 The restricted size of the site meant that limited material stocks could be maintained on site, resulting in some product substitutions and a more widespread use of general purpose tapes, membranes, mastic/adhesives and expanding foam when more specialist materials were not readily available, particularly when sourcing more suitable materials would have resulted in construction delays.

- 16 The pressurisation test results achieved suggest that the targets of $3 \text{ m}^3/(\text{h.m}^2)$ @ 50 Pa for both prototype dwellings and $5 \text{ m}^3/(\text{h.m}^2)$ @ 50 Pa for the existing building are realistically achievable. Although the primary air barrier was well-defined at the design stage for the thin-joint prototype, it often lacked clarity in the other two builds and a number of on-site errors transpired. Performing pressurisation tests at an air barrier completion stage, rather than just on completion, allowed leakage detection and repairs to the primary air barrier to be implemented when the air barrier was still accessible and not obscured by subsequent construction. The experience and increased understanding of airtightness issues resulting from this project has left both of the site teams under the opinion that if they were to repeat this work all three of the dwellings would produce final test results well within these target figures.
- 17 With the airtightness testing conducted by the research team there was greater flexibility in testing than would have been possible had testing been undertaken by an external contractor. With short time windows available for testing and reparatory work, consideration should be given for the clients to develop their own in-house airtightness testing facility as an aid to construction and achieving the more stringent airtightness requirements of low energy housing.
- 18 The engineer's commissioning procedure for the MVHR systems in the prototype dwellings was originally performed only to satisfy Part F of the building regulations, as per the installer's standard protocols. This was inadequate to comply with the M&E consultant's specifications which required the installation engineer to balance the supply and extracts in both standard and boost modes to achieve the energy savings potential of the heat recovery system.
- 19 All three builds were performed with intensive quality control of the build processes. It is perhaps unrealistic to expect the same level of micro-management and concerned party interaction on replication on a much larger scale. Feedback to the design team needs to be maintained throughout any subsequent reproduction, with any on-site modifications or product substitutions ratified by them, if similar levels of performance are to be sustained.
- 20 Many individuals involved in this project will have achieved a significantly increased awareness of how some of the underperforming details can arise and be curtailed. Without an explicit dissemination plan some of the experience and lessons learned from this project might only be passed on to a limited number of individuals directly involved. The existing dwelling site team has since applied some of this knowledge into the subsequent upgrading of an adjacent property in the same street.

Introduction

- 21 This report summarises parts 1 and 2 of the Temple Avenue Project. Part 1 outlines the initial evaluation of the design, construction and performance of two prototype dwellings constructed as part of the development of house type designs for the proposed Derwenthorpe low carbon housing scheme on the eastern edge of York. Part 2 tackles the issues involved in the upgrading of existing dwellings, with the overall aim of establishing the extent to which an existing 1930s masonry house can be renovated so as to achieve a level of performance commensurate with the advanced energy and carbon standard achieved in the prototype new dwellings constructed in part 1 of the project.
- 22 Two prototype dwellings containing some technological innovation were constructed between July and December 2009. One prototype was constructed using thin-joint masonry construction and another using a structural insulated panel (SIPs) build system. The concurrent renovation works to an adjacent existing dwelling explored the impact of two standards of renovation, one reflecting the standard fabric measures that are currently considered to be cost effective and one reflecting the more challenging requirements of an 80% emissions reduction and incurring greater capital costs.
- 23 The project was seen as fulfilling a number of important functions:
- a) To establish and characterise the design and construction issues of meeting the low carbon housing standards required within the context of the two chosen forms of new build construction and in existing dwellings.
 - b) To enable an evaluation of the ease with which the different construction forms are able to meet the required carbon and energy standards and how various refurbishment measures can be applied within the constraints of an existing structure.
 - c) To establish the level of energy and carbon performance achieved in practice and how this compares with theoretical estimates made at design stage. This involved the identification of those features that perform as expected and those that do not.
 - d) To enable modifications to design and/or construction so as to improve the processes involved and dwelling performance prior to replication.
 - e) To provide improved specifications of design and construction, to ensure that replicated dwellings meet or exceed the target standards.
 - f) To provide feedback on performance measurement methods and make recommendations to improve performance control approaches for both new build production cycles and housing modernisation schemes.

Both the Part 1 and Part 2 reports address items a, b & c and, based upon the understandings gained during the evaluation process, and make recommendations as to the most appropriate way forward in areas d, e & f.

Design Assessments

- 24 Design assessments were conducted based on available drawings. Whilst most of the drawings were available at an early stage for the prototype dwellings, the SIPs panel drawings were not released by the manufacturer until a firm order had been received. A full design assessment was not possible for the existing dwelling; where the architects' drawings were based on an initial survey of the dwelling performed in July 2009 whilst the dwelling was still occupied, so was somewhat limited in scope.
- 25 Some of the design issues arising from design assessments of the prototype dwellings:
- a) The short timescale of the project meant construction started prior to full sets of detail drawings, and services designs, being issued.
 - b) Detail design was not comprehensive, with best practicable solutions often having to be developed on site. Commonly, these issues arose at more complex details and junctions, where plans and sections did not provide a full appreciation of the difficulties encountered at 3D junctions.
 - c) Some thermal bridges were missing from the thermal bridging calculations, such as displacement of the slab perimeter insulation by the underfloor vents.
 - d) Continuity of the designed primary air barrier and insulation layer was well indicated on sectional details, but little indication was provided as to how this could be achieved in terms of sequencing and buildability.

- e) Broad design consideration had been exercised to ensure the continuity of both the air barrier and thermal layers. However, potential thermal bypasses remained in several areas where the air barrier and insulation layers were not contiguous.
 - f) The architects attempted to minimise the number of penetrations through the building fabric to aid airtightness and limit repair work, the services designers did not appear to follow this principle so rigorously.
 - g) Services designs regularly placed duct and pipe runs inside insulation layers, displacing insulation and lowering thermal performance.
 - h) A lack of clarity existed between air barrier and vapour control layer arrangements and may have lead to an increased condensation risk if had not identified at such an early stage.
 - i) The specification of membranes often lacked detail of how they should be linked, lapped, or adhered to other building elements, with tapes and fixings usually general purpose recommended by the membrane manufacturer and not substrate specific.
- 26 The 2-stage refurbishment of the existing dwelling, and limited budget, added complications to the design and incomplete detailing. Design assessments were based on GA drawings, and the architects' *Installed Measures* reports and SAP calculation notes:
- a) The initial survey was inadequate for accurate heat loss predictions to be produced for the Phase 1 and 2 coheating tests. The survey was performed with due respect to the occupants, so was as non-intrusive as possible and lead to many assumptions having to be made. Estimates had to be made of many elements and materials where the manufacturer, material composition and exact dimensions, and hence thermal performance, were unclear; SAP 2005 default values were used in instances where there was not enough information to make informed estimates. With the property having undergone extensions to both the side and rear, there were a number of different ground floor and external wall types to be considered and it was not always obvious where the boundaries between these lay.
 - b) The designs included step changes in reducing the airtightness of the dwelling, but there was little detail as to how this was to be achieved. The stage 1 renovation included reducing service penetrations (including removing down-lighters and re-locating the boiler and hot water cylinder to inside the thermal envelope) and the temporary boarding over of the lounge floor, the stage 2 renovation included fitting a new solid ground floor throughout and replacement windows and doors; besides these the airtightness strategy revolved around good workmanship rather than any specific designed-in airtightness measures.
 - c) None of the stage 1 refurbishment insulation upgrades were as simple as similar processes performed in new build. With a number of different external wall constructions, and a high degree of uncertainty about the state of the cavities within these walls, there were likely to be difficulties in the retro-filling of the wall cavities with blown fibre insulation. The lining of the semi-exposed walls in the garage with rigid foam boards was more straightforward, but still involved working around existing fixings. The replacement loft insulation required not only removal of the existing old insulation but also the accumulated debris, obsolete services and loft boarding. The design values did not reflect these difficulties and assumed that all measures taken would achieve their maximum theoretical performance.
 - d) The rear extension roof insulation was moved from ceiling level to rafter level as part of the stage 1 renovations, so it would provide a continuous insulation layer between the stage 2 ground and first floor external wall insulation (EWI). Although this was actually more apposite to the stage 2 renovation, replacing the insulation at ceiling level then discarding it for the next phase was considered imprudent.
 - e) Stage 2 renovations included replacing the ground floor with an insulated concrete slab, fitting 175 mm mineral wool EWI and fitting high-performance triple-glazed windows. These measures involved large costs and disruption, and whilst unlikely to be replicated commonly by occupiers are of greater interest to social landlords looking to raise stock dwellings to higher levels of performance.
 - f) An extension of the eaves was necessary on all 3 external walls to accommodate the additional wall thickness of the added EWI, this also necessitated extending the loft insulation to the top of the EWI to form a continuous thermal layer.
 - g) The placement of the triple-glazed windows was a compromise between thermal performance and structural stability. The replacement windows were considerably heavier than the existing double glazing, but a combination of fixing straps and direct mechanical fixing allowed them to be fitted in line with the existing outer leaf brickwork.

- h) The architects decided to reduce the thermal bridging γ -value in the SAP calculations from the default value of $0.15 \text{ W/m}^2\text{K}$ to the accredited details value of $0.08 \text{ W/m}^2\text{K}$ following the stage 2 renovations, primarily as a result of the EWI, the improved window placement and the extension of the loft insulation to meet the EWI at the eaves.

Construction Observations

- 27 Site visits commenced on all three properties in July 2009, with groundworks in progress on the two prototype dwellings and the existing building still occupied, and continued throughout the build and testing periods enabling a detailed photographic record of both the new build and renovation processes to be developed. Site observations were fed back in the first instance to site management, to substantiate the researchers concerns and assess the practicability of any recommendations by the research team, and through regular contact with the clients and to other interested parties via project meetings.
- 28 Part 1 issues:
- a) The use of expanding foam to fill and cement gaps was prevalent on site but barely mentioned in the designs, in some cases it was used instead of the specified insulation rather than insert small pieces of insulation, it was also commonly and erroneously used as an airtight sealant instead of an airtight material.
 - b) Design modifications made during construction did not undergo the same thorough performance appraisal conducted on the original designs.
 - c) On-site handling issues resulted in damage to a number of edges of the SIPs panels which had to be repaired by the erectors. There were also manual handling issues relating to the thin-joint blocks which were very easily damaged.
 - d) The same mastic/adhesive was used to seal all the gaps between the SIPs panels; whilst suitable for most instances it was not ideal for some of the larger gaps and impossible to inject into many smaller ones. Both examples were commonplace, as many of the gaps between SIPs panels were triangular in shape, some varying in width from 0 mm at one end to up to 15 mm at the other.
 - e) Sequencing and buildability issues reduced the anticipated thermal performance at a number of details. In general these were minor issues, but as target heat loss values fall these will gain in significance.
 - f) Levelling of the sole plates, due to variations in slab levels, with spacers/shims required an injectable grout to be introduced. Access to this was compounded by the presence of membranes and the fitting of internal insulation prior to grouting.
 - g) The fitting of full 1.2 x 2.4 m insulation boards to the thin-joint blockwork, rather than standard sized cavity boards, increased the speed of installation and minimised the taping of joints between the boards.
 - h) Concerns surrounding cracks in the thin-joint blockwork which appeared during construction were allayed by the block manufacturer as natural for this material and not of a concern structurally, advice was supplied by them regarding treatment of such cracks with regard to airtightness.
 - i) The use of trussed rafters in the thin-joint prototype resulted in considerable time and effort expended in maintaining the continuity of the airtightness membrane at roof level, particularly at the eaves junctions and around timbers at the room-in-roof knee walls.
 - j) Potentially innovative design alterations suggested by the site manager were sometimes disregarded in favour of following the design drawings, mainly due to the time constraints both in obtaining the designers' approval and in the procurement process.
- 29 Part 2 issues:
- a) Cavity wall insulation (CWI) was installed as part of the stage 1 renovation by a CIGA approved contractor. The CWI was installed from inside the vacant dwelling using blown mineral fibre insulation using a standard drill pattern, as per the manufacturer's BBA certification. Thermal imaging, heat flux measurements and borescope investigations highlighted issues of variable fill densities and areas of missing insulation, a number of examples of which were confirmed when cavities were exposed as part of the stage 2 renovations. Discussions with the CWI installers resulted in them returning to drill additional holes and inject supplementary insulation, and install a vertical cavity brush at the rear of the property which had been omitted from the original CWI installation.

- b) 400mm of new mineral fibre was installed in the main loft as part of the stage 1 renovation, with the original insulation, services, loft boarding and debris removed. The design suggested the new insulation should be fitted as 100mm thickness rolled out between the joists and a further 300mm laid across this. Instead, two layers of 200mm were fitted, increasing air gaps around the joists and lowering the overall thermal performance of the total insulation layer. The replacement insulation rarely extended right into the eaves to meet up with the wall insulation and form a continuous thermal barrier. The subsequent installation of the MVHR system resulted in disturbance and displacement of the loft insulation which had to be re-laid by the site team.
- c) Opportunities to seal the topes of open cavities and internal partition walls in the short time window between removal of the old loft insulation and fitting of the replacement insulation were missed.
- d) The transformation of the rear extension roof from a cold roof to a warm roof structure was performed “out-of-sequence” with some other renovation work, to allow for some subsequent planned stage 2 renovations. This resulted in increased complexity and some temporary work being necessary, particularly concerning air and vapour barriers. An ‘intelligent’ air tightness membrane was used to regulate the potential for condensation due to variation in its placement in relation to the insulation.
- e) During the stage 1 replacement of the garage ceiling and bedroom 2 floor significant gaps in the inner leaf were exposed, particularly around built-in joists and service penetrations. This prompted the decision to lift the perimeter intermediate floor boards as part of the stage 2 renovations to improve airtightness.
- f) Sealing the open fireplace in the lounge as part of the stage 1 renovations succeeded in reducing air leakage but failed to prevent heat loss through the chimney stack as a substantial thermal bypass remained, this was addressed in the stage 2 renovations.
- g) The increase in airtightness resulting from the stage 1 renovations meant that drying times for wet trades during the stage 2 renovations were significantly increased, with additional heat and ventilation required to drive out the moisture prior to the phase 3 coheating test.
- h) The extension of the roof at the eaves, required to accommodate the EWI, allowed access to the tops of the wall cavities and loft insulation from outside the dwelling, enabling the loft insulation to be topped-up at the eaves to extend it to meet both the CWI and EWI. This was much more effective in creating a continuous thermal barrier than had been possible with the limited access from inside the loft.
- i) Replacement window and door frames were fitted with a vapour barrier attached around the perimeter prior to installation which was returned and taped to the reveals with specialist tape. This proved highly successful in limiting the air leakage at these openings.
- j) Potentially innovative design alterations suggested by the site team were always considered by the project manager, many of which were introduced both on this dwelling and the subsequent renovation of a similar dwelling in the same street.

Airtightness Tests

30 Airtightness test were conducted on the properties at critical stages of the build; both pre-completion and post-construction, and at the beginning and end of each coheating test. Tests were conducted in accordance with the ATTMA TS1/TSL1 protocol (ATTMA, 2007, ATTMA, 2010), results are listed in Table 1, additional details of the airtightness tests are contained within the project Part 1 and Part 2 reports.

Table 1 Pressurisation test results.

Dwelling	Date	Depressurisation Only	Pressurisation Only	Mean Air Permeability	Air Change Rate	Comment
		m ³ /(h.m ²)@50Pa	m ³ /(h.m ²)@50Pa	m ³ /(h.m ²)@50Pa	h ⁻¹ @50Pa	
Thin-joint Prototype	19/10/2009	5.89	5.84	5.87	5.19	Pre-parging
	22/10/2009	5.70	5.42	5.56	4.92	Post-parging
	19/11/2009	4.64	4.02	4.33	3.83	Air barrier completion

	04/01/2010	3.81	4.16	3.98	3.52	Pre-coheating
	04/02/2010	4.00	4.34	4.17	3.69	Post-coheating
SIPs Prototype	25/09/2009	3.33	3.30	3.32	3.06	Air barrier construction
	19/11/2009	2.29	2.53	2.41	2.22	Air barrier completion
	04/01/2010	2.06	2.36	2.21	2.04	Pre-coheating
	04/02/2010	2.28	2.56	2.42	2.23	Post-coheating
Existing Dwelling	01/07/2009	16.50	15.02	15.76	17.41	Occupied dwelling
	06/11/2009	19.99	21.33	20.66	22.82	Post-coheating 1
	07/12/2009	8.97	11.67	10.32	11.40	Pre-coheating 2
	21/12/2009	9.26	10.41	9.83	10.86	Post-coheating 2
	08/03/2010	6.51	6.77	6.64	7.33	Air barrier construction
	10/03/2010	5.58	5.91	5.74	6.35	Pre-coheating 3
	24/03/2010	5.23	5.61	5.42	5.99	Post-coheating 3

- 31 Leakage detection in the thin-joint prototype highlighted the main area of concern as the membrane used throughout the sections of sloping ceiling. Inaccessibility to certain junctions, lack of adhesion to some substrates and unsuitable fixing materials and methods all contributed to greater than expected air leakage through this detail. The physical act of performing the pressurisation tests was enough to exceed the adhesive limits of some of these, with failures observed at pressure differentials of 50~60 Pascals.
- 32 Aside from the above, the airtight performance of the two prototypes was very similar, with the dwellings performing to current good/best practise levels. Air leakage was still detected at openings, penetrations and the complex balcony door detailing, but the attention to detail and understanding of the issues by both the design and site teams are reflected in the good results achieved.
- 33 The pressurisation tests conducted on the prototypes following the coheating tests showed only a minor increase in air leakage, and not a significant increase sometimes observed following the accelerated drying and shrinkage caused by the coheating test procedure. This provides an indication of the robustness of the designed primary air barriers, a lack of over-reliance on secondary sealing measures and the greater potential longevity of the airtight performance of the dwellings.
- 34 The substantial increase in air leakage observed between the first two tests on the existing dwelling were primarily a result of the removal of internal finishings rather than any additional failures in the building structure, particularly the removal of the carpets allowing air to flow more freely through gaps in the suspended timber ground floor and intermediate floor.
- 35 The substantial improvement in airtightness between tests conducted in November and December 2009 appeared to be due mainly to:
- a) The temporary sealing of the suspended timber ground floor and repairs to the intermediate floor in the bathroom and bedroom 2.
 - b) Blocking-up and pointing to the open fireplace in the lounge and re-pointing the internal face of the external bay wall.
 - c) Removal of the external service penetrations for the boiler (originally located in the garage), the hot water cylinder (loft), the bathroom down-lighters and bathroom, kitchen and downstairs WC penetrations to external drains and soil stacks.
 - d) Relocating the air barrier in the rear extension removed air leakage into the rear extension roof void as external air leakage; although penetrations through the rear wall into this void were still sealed to prevent air leakage into the external wall cavity.

- 36 The Stage 2 renovations, between December 2009 and March 2010 saw further substantial reductions in air leakage due mainly to:
- a) Replacing the existing double-glazed windows and doors with high performance doors and triple-glazed windows.
 - b) Ripping up the existing ground floor and replacing with a solid concrete insulated ground floor.
 - c) Lifting the intermediate floor perimeter boards to seal gaps around built-in joists and penetrations.
 - d) Replacing the access hatch to the main loft with a proprietary draught-stripped loft hatch.
 - e) Performing a pre-completion pressurisation test in early March 2010 to identify air leakage paths prior to completion of the internal finishings and decoration; leakage detection identified areas around newly installed services such as the new boiler, solar hot water and loft-mounted MVHR system, and at thresholds and unfinished details.
- 37 Some air leakage identified in the final test on the existing dwelling was due to be addressed at a later date to reduce the airtightness to below the target $5 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50 \text{ Pa}$, this included finishing around the rear door (after the replacement for the incorrectly supplied one had been fitted), draught-stripping of the kitchen to garage door, and decoration, caulking and some additional sealing work of joints, junctions and penetrations caused by natural settlement and shrinkage.

Coheating tests

- 38 Coheating tests were performed on the prototype dwellings shortly after completion, and on the existing dwelling prior to any renovation and immediately following each of the stage 1 and 2 renovation processes. Coheating tests were conducted according to the protocol outlined by the whole house heat loss test method (coheating) developed by Leeds Met (Wingfield et al., 2010), the results are displayed in Table 2 and Figure 1, additional details of the coheating tests are contained within the project Part 1 and Part 2 reports.

Table 2 Coheating test results.

Coheating Test	Start Date	End Date	Predicted Heat Loss Coefficient W/K	Measured Heat Loss Coefficient W/K
Thin-joint Prototype	04-Jan-09	04-Feb-10	124	149
SIPs Prototype	04-Jan-09	04-Feb-10	120	133
Existing Phase 1	20-Oct-09	06-Nov-09	341	312
Existing Phase 2	07-Dec-09	21-Dec-09	239	242
Existing Phase 3	10-Mar-10	24-Mar-10	107	147

- 39 A credible comparison between measured and predicted heat loss (as shown in Table 2) relies on the accuracy of both datasets. Whilst the predicted heat loss coefficients for the prototype dwellings were based on conscientious scrutiny of detail design drawings by the architects; this was not possible for the existing dwelling (particularly for the Phase 1 and 2 coheating tests), where numerous assumptions of the construction were necessitated, resulting in a far greater degree of uncertainty over the predicted heat loss value quoted. Scheduling all the coheating tests, and the 2-stage renovation works on the existing dwelling, into a single winter involved careful planning and resulted in the initial and final tests on the existing dwelling being performed outside of the ideal time window, when warmer external temperatures and increased solar insolation were more likely to affect the accuracy of the data obtained. Initial warming and drying periods at the start of each coheating test are not included in the analysis of the data. Similarly, some days when access to the houses was required by the client, and data compromised, have also been omitted from the analysis.

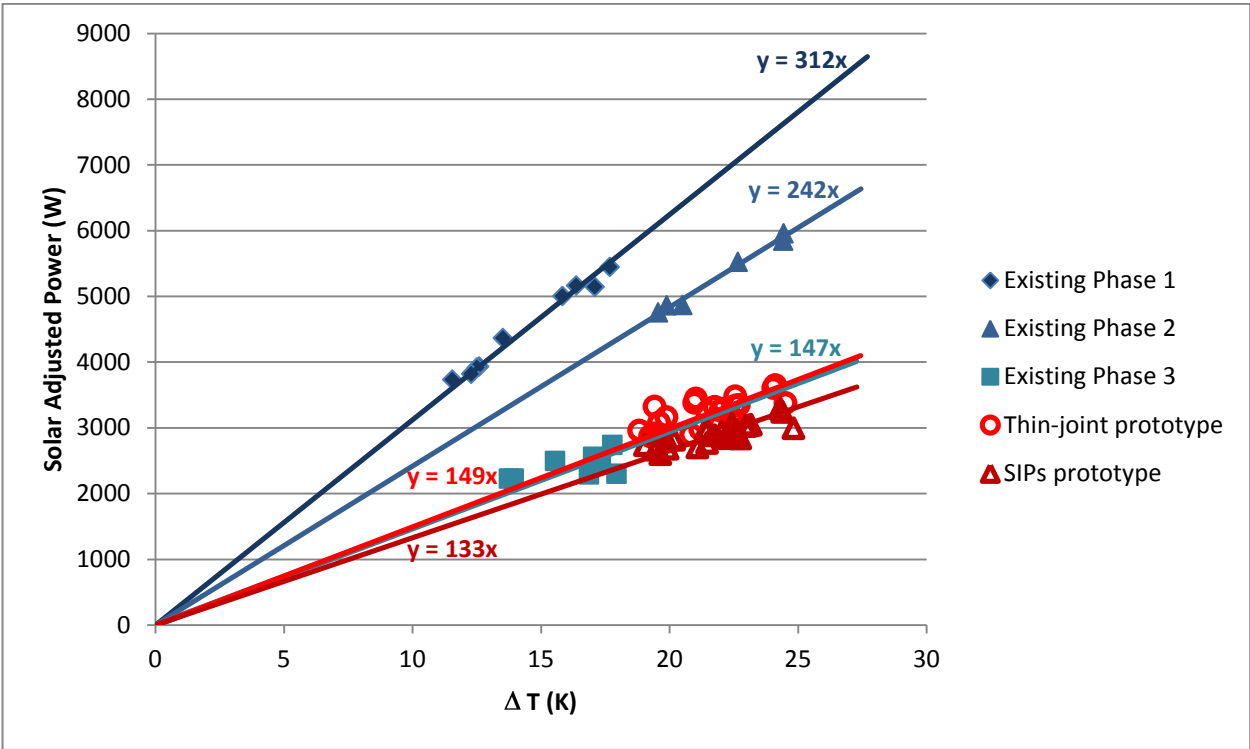


Figure 1 Coheating test results – measured heat loss coefficients..

- 40 What is immediately obvious from Figure 1 is the success of the refurbishment of the existing dwelling in reducing the fabric heat loss by over 50%, with improved systems performance and solar hot water this helps in almost achieving the design reduction in CO₂ emissions of 80%. The combined effect of the stage 1 and 2 renovations brings the heat loss coefficient to a level commensurate with the two prototype dwellings, which were also 3 bedroom family homes albeit larger. The SIPs prototype outperformed the thin-joint prototype by about 10%, possibly not much greater a difference than the potential for experimental error inherent within in the coheating test methodology.
- 41 With the three coheating tests on the existing dwelling performed over one heating season, it was possible to compare the effect of solar gains on the test methodology itself. The adjustments necessary for solar correction of 15.4 W/K (initial phase), 3.5 W/K (phase 2), 12.3 W/K (phase 3) reflected the test dates, with the initial phase coheating test commencing in October, phase 2 in December and the phase 3 coheating test performed in March. The larger corrections necessary relate to the extended daylight period and solar intensity occurring in October and March, for the phase 3 test in March this represented an increase of nearly 10% on top of the metered electricity supplied to the dwelling during the test, in a dwelling which was not orientated to maximise solar gain. With lower energy dwellings orientated to maximise solar gain the size of this correction would be proportionately larger and may limit the coheating test window to November to February, or demand some amendment to the protocol to introduce some solar shielding if tests are to be performed outside this period.
- 42 To put the Temple Avenue coheating test results into context Figure 2 compares the variation in measured heat loss over predicted performance of dwellings tested by the Leeds Met research team up to March 2010 prior to such interventions as retro-filling of party wall cavities. The SIPs prototype is on a par with the best performing timber framed dwellings, whilst the thin-joint prototype performs closer to the design values than any other masonry dwellings tested. The Phase 3 coheating test on the existing dwelling also displayed a lesser degree of underperformance of the building fabric than any of the mass-produced, speculative, new-build housing which was designed to Part L 2006 standards, or better, included in the dataset.

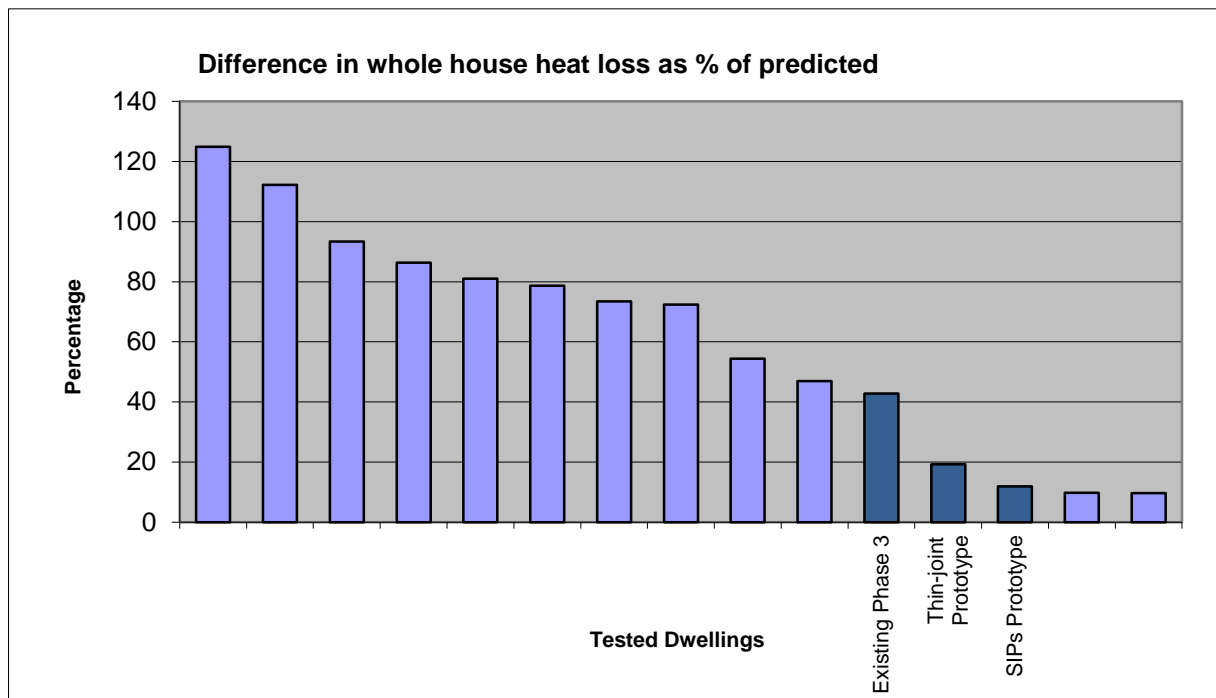


Figure 2 Variation between predicted and measured heat loss coefficients on dwellings tested by Leeds Met between December 2005 and March 2010 prior to interventions.

43 To gain information on where the additional heat losses displayed in Table 2 were occurring, heat flux measurements were used to derive in-situ effective U-values of a number of heat loss elements throughout the course of the coheating tests. The mean daily U-values obtained are listed in Table 3 alongside the design-prediction U-values and the range of the derived measured values. Due to the limited number of heat flux sensors available, the measured U-values obtained are only indicative of the total area U-values, a much greater density of sensors would be required for accurate analysis. The results acquired are analysed in greater detail in the individual project Part 1 and Part 2 reports.

Table 3 Predicted and daily average U-values derived from heat flux measurements.

Element	Existing Phase 1		Existing Phase 2		Existing Phase 3		Thin-joint Prototype		SIPs Prototype	
	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured
	W/m ² K	W/m ² K	W/m ² K	W/m ² K	W/m ² K	W/m ² K	W/m ² K	W/m ² K	W/m ² K	W/m ² K
Windows (centre pane)	-	-	-	-	0.5	0.51 0.44-0.59	1.272	1.30 1.23-1.35	1.263	1.32 1.27-1.36
Solid Ground Floor	0.881	1.04 0.69-1.44	0.881	-	0.195	0.31 0.27-0.35	0.155	0.15 0.06-0.27	0.155	0.18 0.12-0.33
Suspended Timber Ground Floor	0.365	1.24 0.31-1.93	0.365	1.01 0.82-1.34	-	-	-	-	-	-
Intermediate Floor above Garage	0.253	-	0.200	0.18 0.11-0.31	0.200	0.15 0.11-0.17	-	-	-	-
External Wall	1.014 0.65-1.68	1.50 0.54-2.27	0.576 0.45-0.65	1.12 0.66-1.73	0.150	0.42 0.19-0.77	0.170	0.30 0.18-0.52	0.150	0.19 0.14-0.27
Internal Cavity Wall	0.00	0.52 0.44-0.64	0.00	0.15 0.06-0.31	0.00	0.02 -0.01-0.07	-	-	-	-
Party Wall	0.00	0.44 0.17-0.70	-	-	-	-	-	-	-	-

Sloping Ceiling	-	-	-	-	-	-	0.155	0.11 0.09-0.14	0.150	0.21 0.18-0.27
Ceiling	-	-	0.11	0.34 0.22-0.45 (under joist)	-	-	-	-	-	-

- 44 The predicted U-values listed in Table 3 are either manufacturer’s quoted figures (windows) or basic steady state approximations calculated from empirically determined material properties, the measured figures portray the average daily heat flux measured through those elements divided by the average daily internal/external ΔT . Variations in the measured U-values were observed due to a number of factors, including; sensor placement, build anomalies, external environmental conditions and thermal bypassing and heat recovery resulting from bulk air movement behind the surface to which the heat flux sensor was attached. Sensor placement was determined using thermal imaging to identify the areas where heat loss appeared to be representative of the area, or at both extremes of performance.
- 45 Table 3 also indicates that the greatest level of variation in measured thermal transmittance was for the suspended timber ground floor of the existing dwelling (after phases 1 and 2 this was replaced with a solid floor) and the external walls. When the areas over which these U-values apply are taken into consideration there may be considerable differences between the heat losses presumed for individual building elements and those achieved in reality. Figure 1 compares the measured whole house heat loss obtained for each coheating test which cannot be accurately divided and apportioned to discrete building elements without a far more intensive measurement regime than fell under the scope of this project. Segregation of the heat loss to different elements is, however, performed for the predicted values (e.g. in SAP calculations); Figure 3 displays these and shows how each element contributes to the overall house heat loss, and helps in understanding where variations in measured heat loss can have the greatest impact on attempts to analyse the heat loss mechanisms affecting the test results. In the case of the existing dwelling, a chart such as Figure 3 usefully indicates where the greatest possibilities for improvement may lie; the stage 1 renovations to ceilings and walls were predicted as the most cost-effectives energy saving opportunities, the heat flux measurements revealed that these only met with partial success in practice. Figure 3 also suggests that the more capital intensive measures performed in the stage 2 renovation of the existing dwelling are essential to reduce heat loss to levels comparable to modern low carbon housing; with the replacement insulated floor, EWI and triple glazing driving down the predicted elemental heat loss to the required levels of performance.

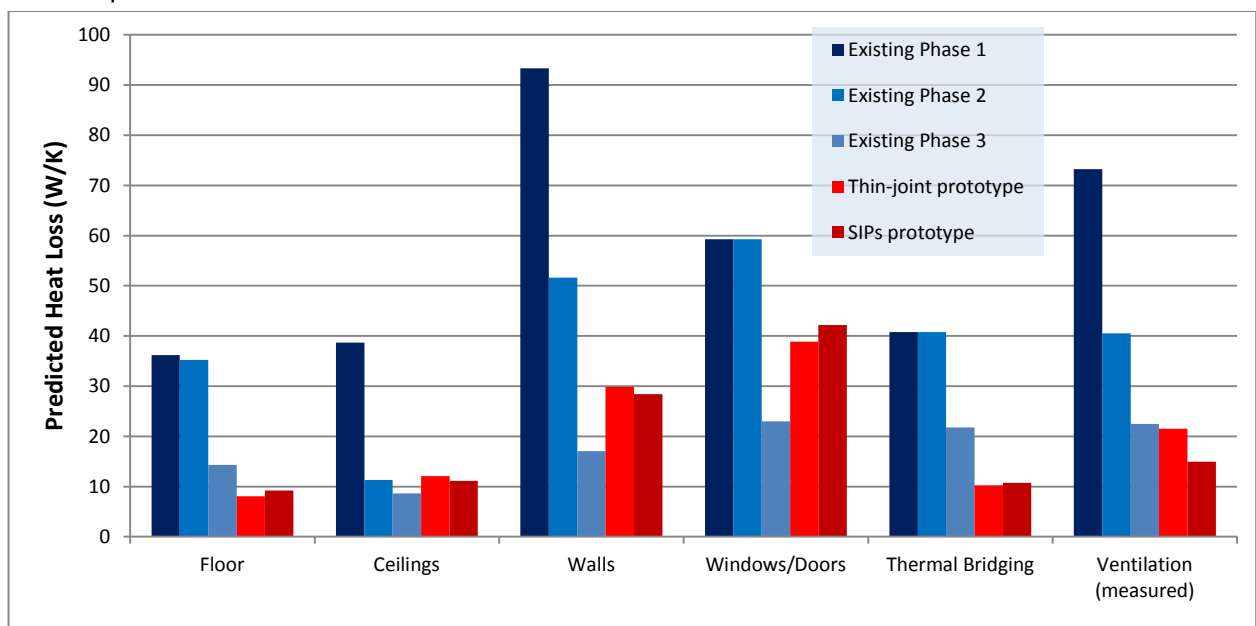


Figure 3 Predicted total heat loss through individual building elements.

- 46 The ventilation heat loss shown in Figure 3 is based on actual mean pressurisation test results rather than target air leakage rates. With lower levels of fabric heat loss the proportion of overall

- dwelling heat loss attributable to ventilation increases accordingly. CO₂ concentration pulse and decay measurements taken throughout the coheating tests confirmed that the mean of air leakage rates measured at the start and end of each coheating test was representative of the average daily air leakage rate and no significant step changes in airtightness occurred during the tests.
- 47 As the existing dwelling was semi-detached it was necessary to make adjustments to the coheating test results for heat loss across the party wall. Based on the temperature differences between the lounge in the adjoining property and the constant internal 25°C of the test property, and heat flux measurement of the party wall, a nominal daily value of 160W was subtracted from the solar-corrected power consumption to account for heat loss through the party wall in the phase 1 coheating test. With only slight variations in average inter-dwelling ΔT and party wall area for the two subsequent tests the same adjustment value was used, so any inaccuracy of the nominal figure used is repeated for all three coheating tests on the existing dwelling and effectively cancelled out when examining differences between each of the three coheating test results.
- 48 Thermal imaging, heat flux measurement and stand-alone temperature loggers were used to confirm that thermal bypassing was occurring in the internal cavity walls in the phase 1 coheating test on the existing dwelling. The side and rear extensions to the property converted previously external cavity walls to internal cavity walls, which were open to the external wall cavities and the loftspace. U-values greater than 0.6 W/m²K were obtained for these walls prior to any renovation work, filling the cavities with CWI reduced this figure to around 0.1 W/m²K. Adding the EWI (which also allowed the tops of the external wall cavities at the eaves to be plugged with mineral wool) and a solid ground floor further reduced their U-values but did not eliminate the heat loss entirely.

MVHR Systems

- 49 In addition to the building fabric; the design, installation and commissioning of the ventilation systems were also monitored by the research team. A number of issues arose relating to the systems installation both from site observations and from measurements of flow rates at supply and extract grilles following commissioning.
- The terminal vents originally fitted in the prototype roofs were deemed inadequate by the MVHR engineer for the airflows required, prior to installation of the systems. This resulted in new terminal vents being fitted.
 - Fitting of the duct-work in both the existing dwelling loft and the sloping roof section of the thin-joint prototype involved disruption and displacement of insulation, reducing the thermal performance of the roof structures.
 - Although the use of rigid duct-work was prioritised, the fraction of flexible duct-work used in all three installations was greater than designed.
 - In the thin joint prototype the duct-work was performed prior to parging of the internal blockwork, and penetrated the air barrier membrane in the sloping roof section in a number of instances. This added complexity to maintaining continuity of the air barrier, increasing the likelihood of air leakage.
 - Commissioning certificates were issued for the prototypes' MVHR systems in December 2009 by the manufacturer/installer, subsequent flow rate measurements by the research team highlighted discrepancies in the measurements and no balancing of supply and extract. Re-commissioning took place and revised certificates issued in February 2010. Additional tests revealed further discrepancies and re-revised certificates issued in March 2010 with the systems finally fully commissioned to a standard acceptable by the M&E engineer.

Conclusions and Recommendations

- 50 Many of the issues raised in this report are due to the fact that the two new-build properties were prototype dwellings, and the refurbishment of the existing dwelling was performed as a prototype refurbishment. The Temple Avenue project was a learning process, and modifications to the designs as construction progressed were to be expected. This project covers only issues relating to the fabric performance of the dwellings and does not attempt to evaluate the full efficacy of the designs and builds with regard to CO₂ emissions.

Design

- 51 The 2 stage renovation of the existing dwelling caused some additional complications to the design process. Additional costs and design considerations were incurred as a result of this 2 stage renovation process and prevent any simple cost benefit analysis of many of the individual measures introduced.
- 52 The initial assessment of the existing dwelling was conducted with the dwelling still occupied and the survey conducted in a manner which, understandably, caused minimum disruption to the occupants. As models and calculations require a higher degree of accuracy a more intrusive investigation would have been beneficial. Some incorrect assumptions made regarding the initial fabric performance may have been more accurate if the initial survey had been performed after the dwelling had been vacated, with the surveyors less sensitive any aesthetic damage and subsequent repair work required.
- 53 A number of issues are raised in the Part 1 and Part 2 reports relating to design, these include:
- a) Issues relating to process and sequencing should be more prominent in the design, particularly where construction needs to be performed "out-of-sequence" as far as the traditional sequence of trades and fixes is concerned.
 - b) The designers detailed drawings should also include those of services, to help eliminate discrepancies between different sets of drawings supplied to different contractors. This could assist in solving certain sequencing concerns, and issues such as insulation displacement by pipe/duct-work could either be designed out or included in the thermal calculations.
 - c) The designs and specification of membranes, tapes, filling materials, adhesives and sealants requires further clarification.
 - d) Although the wall insulation in the thin-joint prototype was generally very well-fitted, air movement around the insulation boards still persisted at junctions, edges, openings and penetrations which all reduced its effectiveness. The designs should to provide instruction on how this can be minimised wherever this is likely to occur.
 - e) Also in the thin-joint prototype, considerable difficulties maintaining the integrity of the roof membrane around trussed rafters was not taken into account on the sectional drawings. If both TS and LS section drawings were available this may have raised awareness of these difficulties at the design stage.
 - f) No primary air barrier was identified on the details for the SIPs prototype, occasionally causing confusion over where the sealing of joints and penetrations was most appropriate. The addition of an air tightness membrane would add conceptual clarity as to what constituted the air barrier and where sealing should be performed.
 - g) There was a lack of information available for the existing dwelling to show how a continuous thermal barrier would be achieved at the eaves as part of the stage 1 renovations, given that access to the eaves was severely limited from inside the loft. Such description of build process is perhaps not expected in a project of this size and nature, particularly where design costs are limited, but may require more regard if these processes are to be replicated.
 - h) The designed existing building renovations appeared not to fully appreciate the full effects of potential thermal bypassing throughout the property. Specific edge sealing of the cavities (and the tops of first floor partition wall voids) was not always possible, and where possible was not prioritised, which would have reduced the likelihood and severity of any potential bypasses.
 - i) A full analysis of thermal bridging was not performed for the existing dwelling and a SAP default y-value of 0.15 W/m²K applied for the phase 1 and 2 coheating tests; a y-value of 0.08 W/m²K was adopted following the stage 2 renovations. Full thermal simulation of the details would have been prohibitively expensive, but whether these values were appropriate for each respective stage of construction is uncertain and simulation of a small number or selected details would have provided useful information on whether the y-values used for each stage were appropriate. Thermal imaging surveys suggested that the EWI was extremely effective in substantially reducing, or even effectively eliminating, many of the thermal bridging problems relating to the external walls, but without any appropriate modelling and more intensive measurements it was not possible to quantify the improvements observed.

Construction Process

- 54 The involvement of the Leeds Met research team had an effect on the project programming, with the schedule needing to be adapted to fit all the coheating tests into one heating season and performing all renovation work on the existing dwelling between these periods. This did present

- some difficulties for the refurbishment of the existing dwelling and was worked around by the project manager and site team, with temporary fixes and break-ins kept to a minimum to avoid unnecessary costs. The decision to perform the 2 stage refurbishment added further complications to the build sequence and programme. It would have been easier, and cheaper, to perform all the refurbishments in a single phase, but the 2 stage refurbishment allowed greater insight into the effectiveness of each of the measures introduced.
- 55 Regular contact was maintained between all concerned parties, particularly during busy periods and some of the more critical stages of construction. This can be regarded as one of the successes of the project; it is difficult to see how some of the issues would have been resolved without such effective communication.
- 56 Issues raised in the Part 1 and Part 2 reports following observations of the construction include:
- a) The restricted size of the site meant that limited material stocks could be maintained on site, resulting in some product substitutions which may not occur on replication on a larger scale. This may also explain the widespread use of general purpose tapes, membranes, mastic/adhesives and expanding foam when more specialised materials and components were not at hand or readily available, particularly when sourcing more suitable materials would introduce construction delays.
 - b) Variations in the levels of the ground floor slabs for the prototype dwellings caused little problem in the thin-joint prototype, as the small deviations were easily absorbed into the block courses, but resulted in un-designed adjustments in the erection of the SIPs panel system. The differences in tolerances between trades on the SIPs prototype required additional sealing materials and labour to resolve and may have resulted in additional air leakage and thermal bridging at the wall/floor junctions.
 - c) By using larger boards and not requiring wall ties to be built-in by the block-layers, the wall insulation fixing method for the thin joint prototype was quick to install and minimised the taping of joints between the insulation panels, particularly on the large, uninterrupted gable walls.
 - d) Although the cracks that appeared in the thin-joint blockwork during construction were deemed non-structural by the manufacturer and made airtight by the parging layer, if new cracks were to appear post-parging and dry-lining (or existing ones expand) these would be difficult to detect¹ and would not be repairable without considerable cost.
 - e) The unparged thin-joint blocks presented unforeseen adhesion problems due to their surface properties. This highlights the need for the parging layer to be complete at an early stage, and may explain why only partial success of the tanking strips used on the external side of the blockwork was achieved for airtight sealing of wall penetrations.
 - f) The installation of the CWI in the existing dwelling met with limited success due to incomplete fill of the cavities, even though the fill process appeared to be mainly in accordance with BBA and CIGA recommended procedures. Without the involvement of the research team in this project the lack of insulation in large areas of the walls, and subsequent thermal underperformance, may not have been detected. It is unlikely that this is a one-off occurrence and there could be very many similar properties nationwide where these issues have been repeated, properties where both clients and installers alike remain unaware of the lack of success of their efforts.
 - g) The designed replacement loft insulation in the existing dwelling of 100 mm thick mineral wool quilt between the joists and 300 mm thick quilt running normal to this was replaced by 2 layers of 200 mm thickness. This had the effect of increasing the air gaps in the insulation layer around the ceiling joists and so reducing the thermal performance.

Airtightness

- 57 The pressurisation test results achieved suggest that the targets of $3 \text{ m}^3/(\text{h.m}^2)$ @ 50 Pa for both prototype dwellings and $5 \text{ m}^3/(\text{h.m}^2)$ @ 50 Pa for the existing building are realistically achievable. The experience and increased level of understanding of airtightness issues resulting from this project has left both of the site teams under the opinion that if they were to repeat this work all three of the dwellings would produce final test results well within these target figures.
- 58 Some of issues raised regarding airtightness include:
- a) Although the air barrier was well-defined in the design for the thin-joint prototype, it lacked clarity in the other two builds. Mistakes were made, such as sealing windows to the breather

¹ Detection of such cracks in the blockwork may be detectable using a thermal imaging camera under dwelling depressurisation, providing a suitable internal/external ΔT exists.

membrane in the SIPs prototype instead of to the air barrier and discontinuities in the air barrier at the garage ceiling in the existing dwelling, which would have been less likely if the primary air barrier had been more clearly defined.

- b) Air leakage detection performed on the prototype dwellings showed the thin-joint prototype displaying more leakage around the sloping roof sections and through trickle vents, and the SIPs prototype performing worse at the ground floor/external wall junctions and around openings. Performing pressurisation tests at an air barrier completion stage, rather than just on completion, allowed leakage detection and repairs to the primary air barrier to be implemented when the air barrier was still accessible and not obscured by subsequent construction. Where low levels of air leakage are sought this additional testing needs to be included in the build programme.
 - c) The lack of reliance on secondary sealing in the completed dwellings was confirmed by the small increases in air leakage observed in tests performed at either end of the coheating tests, Maintaining the high internal temperatures necessary for the coheating tests has been shown to accelerate drying and shrinkage and cause partial failure of secondary sealing, leading to much larger increases in air leakage than was observed in this project.
 - d) With the airtightness testing conducted by the research team there was greater flexibility in testing than would have been possible had testing been undertaken by an external contractor. With short time windows available for testing and reparatory work, consideration should be given for the clients to develop their own in-house airtightness testing facility as an aid to construction and achieving the more stringent airtightness requirements of low energy housing and dwellings where higher levels of airtightness are demanded for the efficiency of MVHR systems.
- 59 Specific areas remained in all three dwelling where improvements to the airtightness could have been achieved:

The main areas for improvement in the masonry prototype:

- a) Membranes – these should be fit for purpose and installed in the correct sequence using suitable fixings and tapes.
- b) Trickle vents – if these are to be installed they should be of the type with a compressible airtight seal.
- c) Parging layer – this needs to be complete and applied prior to any 1st fix installations.
- d) Window and door frames – these need to be robustly sealed to the structure at jambs, heads and sills/thresholds.

The main areas for improvement in the SIPs prototype:

- e) Slab perimeter – even though a lot of effort was exerted returning membranes and sealing there was air leakage at many points around the ground floor perimeter.
- f) Threshold build sequence – not filling the cavity and sealing the thresholds until after the dry lining and skirting boards had been fixed left areas at either side of the threshold inaccessible and virtually impossible to seal retrospectively.
- g) Breather membrane at openings – taping the window frames to the breather membrane rather than the wall/roof panels appeared allow significant direct air leakage around many openings.

In the existing dwelling following the stage 2 renovations:

- h) Ground floor perimeter – particularly at unfinished junctions (such as behind kitchen units) and at thresholds.
- i) External doors – unfinished details remained around the external and garage doors at the time of the final test.
- j) Lofthatch – leakage remained between the door and trap and between the ceiling and lofthatch surround.
- k) Intermediate floor perimeter – issues remain around the offset edge joist and the expanding foam used to seal around built-in joists not fully filling the gaps.
- l) 1st Floor ceiling penetrations – many of these proved difficult to seal from inside the habitable space due to access problems.
- m) 1st Floor partition wall heads – these can only be effectively sealed from inside the loft, the opportunity to do this was not undertaken.

- n) Junction of intermediate floor with old gable wall – the opportunity to fully close the link between the open cavity and the floor void when the landing floor was lifted was missed.

Thermal Performance

- 60 Using a comparison of measured vs. predicted heat loss as an indication of the dwellings' fabric performance relies on the accuracy of both sets of data, this is difficult to achieve, particularly in the case of predicted values for the existing dwelling. As the predicted heat loss relies on theoretical performances of materials installed ideally, it is highly unlikely that the predicted performance will be fully achieved in practice. With dwellings designed for low levels of heat loss, displaying the difference as a percentage of the predicted heat loss is unfavourable when compared to the percentage deviation of less thermally efficient dwelling. Even taking this into account, all three dwellings were amongst the best performing dwellings tested by Leeds Met in terms of lowest levels of underperformance.
- 61 Measured heat loss coefficients from the coheating tests are representative of the predicted values but do display some variation. Whilst for the case of the phase 1 and 2 coheating tests on the existing dwelling it is suggested that these variations are mainly due to inaccuracies in the predicted values, due to the number of assumptions of the original construction; variations for the phase 3 coheating test result on the existing dwelling and for the tests on the prototype dwelling were primarily due to the realised level of thermal performance not achieving that set out in the designs.
- 62 The adjustments necessary for solar correction in the existing dwelling of 15.4 W/K (initial phase) and 12.3 W/K (phase 3) reflected the test dates, with the initial phase coheating test commencing in October and the phase 3 coheating test performed in March. For the phase 3 coheating test this represented a 9% increase over the raw measured heat-loss coefficient due to solar insolation, any coheating tests performed later in the Spring would inevitably require even larger solar adjustments which may start to overwhelm certain aspects being investigated. This would particularly be the case if the test dwelling was orientated to maximise solar gain and have an increasing influence on dwellings with a lower heat-loss parameter. External temperatures as high as 17.9 °C and 14.8 °C were recorded in the initial phase and phase 3 coheating test periods respectively, shortly outside these test periods (in September 2009 and April 2010) external temperatures in excess of 20 °C were recorded. The combination of both these solar effects and ΔT effects prescribe the seasonality of the testing period, and should be the foremost criterion when planning any future coheating tests.
- 63 The measured heat-loss coefficients for the 3 phases of coheating on the existing dwelling provided effective mean fabric U-values of 0.99 W/m²K for phase 1, 0.77 W/m²K for phase 2 and 0.47 W/m²K for phase 3. The phase 3 result compared slightly unfavourably to the mean U-values for the prototype dwellings of 0.44 W/m²K (Thin-joint) and 0.37 W/m²K (SIPs), but the difference was not enormous and would reduce further upon full completion of the renovation work on the existing dwelling. The phase 3 test result was achieved with unfinished detailing which would reduce the final fabric heat loss on completion with additional airtightness improvements potentially reducing the final amount of heat loss attributable to ventilation.
- 64 A number of issues developed regarding thermal performance, including:
- a) The application of EWI to the existing dwelling saw significant reductions in all areas where U-values were measured, although the design figure of 0.15 W/m²K was never achieved.
 - b) Heat flux measurements recorded during the coheating tests showed that the combined effect of the CWI and EWI virtually eliminated the thermal bypassing identified in the internal cavity walls in the existing dwelling, even though improvements in the external wall performance were not as good as was expected.
 - c) From the heat flux measurements on the prototype dwellings it would appear that the designed U-values of the walls and sloping ceilings are minimums rather than average U-values and the effects of air movement at edges and openings are far greater than predicted, particularly in the masonry prototype. Reducing the air movement around the insulation at these details is important if the design U-values are to be approached more consistently.
 - d) Internal temperatures on the south facing facades of the prototype dwellings were observed to overshoot the 25°C set point by up to 3K on days with prolonged unbroken sunshine, when external temperatures were still below 5°C; this gives an indication of the likelihood that high internal temperatures in the Summer may be a problem

Systems Performance

- 65 The engineer's commissioning protocol for the MVHR systems in both of the prototype dwellings was originally performed only to satisfy Part F of the building regulations (achieving minimum totals of trickle supply and boost extract) and not to the M&E consultant's specifications. More particularly, no effort appeared to be made by the installation engineer to balance the supply and extracts in either mode to achieve the energy savings potential of the heat recovery system.
- 66 No client would reasonably assume that the information supplied on official commissioning certificates would be inaccurate yet, in the case of the prototype dwellings, this was found to be the case on a number of occasions. By contrast, the measurements taken by the commissioning engineer for the MVHR system in the existing dwelling were virtually identical (to within experimental error) of those recorded by the Leeds Met research team, and met all the design criteria fully. It may be wise to perform regular independent checks of certain systems and not to take the performance of services at face value.

Replication

- 67 All three builds were performed with intensive quality control of the build processes, with numerous formal and informal visits to site made by various parties involved in the project and constant contact between site operatives and management, project management, clients, designers and the research team. This type of micro-management and concerned party interaction is unlikely to occur on replication on a much larger scale.
- 68 Some of the experience and lessons learned by the project team, from management through to site operatives, during both renovation and new-build may only be partially documented, and may only be read, passed on or disseminated to a limited number of individuals within their organisations. Many individuals involved in this project will have achieved a significantly increased awareness of how some of the underperforming details can arise and be curtailed. The existing dwelling site team has since applied some of this knowledge into the subsequent upgrading of an adjacent property in the same street.
- 69 With the project being undertaken as a research project ad hoc design changes and modifications were anticipated, as such a full set of design details was not available for either stage of the existing dwelling renovations. However, it would be extremely useful to have detailed drawings of the final construction to show what had actually been constructed and to allow for these evolved details to be used again, or adapted, for future renovations and refurbishments of similar dwelling types.
- 70 A number of suggestions regarding replication of the prototype builds and renovation on a much larger scale are listed in the individual Parts 1 and 2 project reports, these include:
- a) Drawings should be compared for consistency to avoid ad hoc design decisions having to be made on site. They should include more sequencing and process detail.
 - b) Specifications of tapes, membranes and adhesives should be improved, with installers made aware of minimum laps, surface preparation procedures and how to work around complex details.
 - c) The unspecified use of expanding foam as an airtight substrate or insulation material should be reduced and specified components, sealants and insulation used.
 - d) Air movement around rigid board insulation was observed to diminish its performance. This could be reduced by bonding the insulation to the walls rather than a pure reliance on mechanical fixing, as was observed with the EWI on the existing dwelling.
 - e) The SIPs panel jointing could be improved significantly by adopting rebated gaskets which would provide seals through the entire depth of the wall and would allow for better minor repositioning than the observed method of double beads of adhesive. As damage to SIPs panel edges, and other materials, caused by handling issues may well increase in large scale replication, a rebated panel link may also be easier to repair robustly.
 - f) Window restraint straps resulted in some additional thermal bridging, difficulties in sealing for airtightness and additional work to board out the jambs. Fitting the windows in a plywood box detail, which filled the opening and could be more simply sealed to the structure, would reduce such problems.
 - g) Feedback to the designers needs to be maintained throughout, with any on-site modifications or product substitutions ratified by them.

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