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

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Introduction

1 This report 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, and is designed to complement part 2 of the Temple Avenue Project (Miles-Shenton et al., 2011) which tackles the issues involved in the upgrading of an existing dwelling

Background

2 Two prototype dwellings containing some technological innovation were constructed between July and December 2009. One prototype (A1) was constructed using thin-joint masonry construction and another (A2) using a structural insulated panel (SIPs) build system.

3 The construction of the prototype dwellings 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 construction.

b) To enable an evaluation of the ease with which the different construction forms are able to meet the required carbon and energy standards.

c) To enable the performance of the dwellings types and construction forms to be established prior to replication and to characterise those features that contribute to the level of performance observed.

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 the main production cycle.

This preliminary report addresses items a, b & c and, based upon the understandings gained during the evaluation process, makes recommendations as to the most appropriate way forward in areas d, e & f.

Evaluation

4 The evaluation in this preliminary report follows two of the objectives outlined in the original project proposal:

a) Evaluation of the construction process through site observations and a review of detailed construction information and how it was applied by the site teams.

b) Measurement of the performance of the dwelling fabrics and, where possible, evaluation of the expected performance of dwelling services based on observations of installation together with commissioning data and other documentation.

5 The as-constructed measurements of the performance characteristics of the thermal envelope of each dwelling are compared with predicted performance and the factors deemed to have contributed to the observed performance levels suggested. Measurement of services performance can only be obtained through in-use or simulated in-use measurement; however, it was possible to measure basic flow rates in the ventilation system.

6 Measurement of fabric and services includes the following:

a) Airtightness – measured prior to and following air barrier completion, with additional tests carried out at the beginning and end of the co-heating tests and ventilation rate throughout the coheating test calculated from tracer gas decay.

b) Fabric heat loss – measured by undertaking a co-heating test of each dwelling, with additional measurements taken including heat flux readings to ascertain effective U-values at select locations.

c) Services – a comparison of commissioning data and measured supply and extract rates of the ventilation system was performed.

Design assessment

7 A brief assessment of design was performed prior to the construction based on drawings available at the time. Issues were raised at pre-construction meetings particularly regarding air barrier

positioning and continuity which were fed back to the architects and main contractors, and either alterations or additional clarifications carried out. Some of these issues related to the sequencing of construction, where the buildability of the design presented potential problems or appeared to display ambiguities.

8 Inevitably there were some details missing from the drawings which required to be made up on site. The accessibility of the architects and communication between them and the site manager allowed best practicable solutions to be achieved quickly, however it is unclear as to whether all these discussions resulted in amendments to the designs.

9 Some design issues were resolved on site following discussions between the site and design staff. Thermal bypasses arise where the air barrier and insulation layer have become separated. The potential thermal bypass in the A1 (masonry) prototype, in the area ringed in Figure 1, linked the void beneath the ground floor to the roof void; it was resolved by fully filling the void with insulation and a membrane used to ensure that the top of the void was closed off before it linked to either the roof void or the intermediate floor void. This solution was agreed between the architect and site manager after discussing a number of different options.

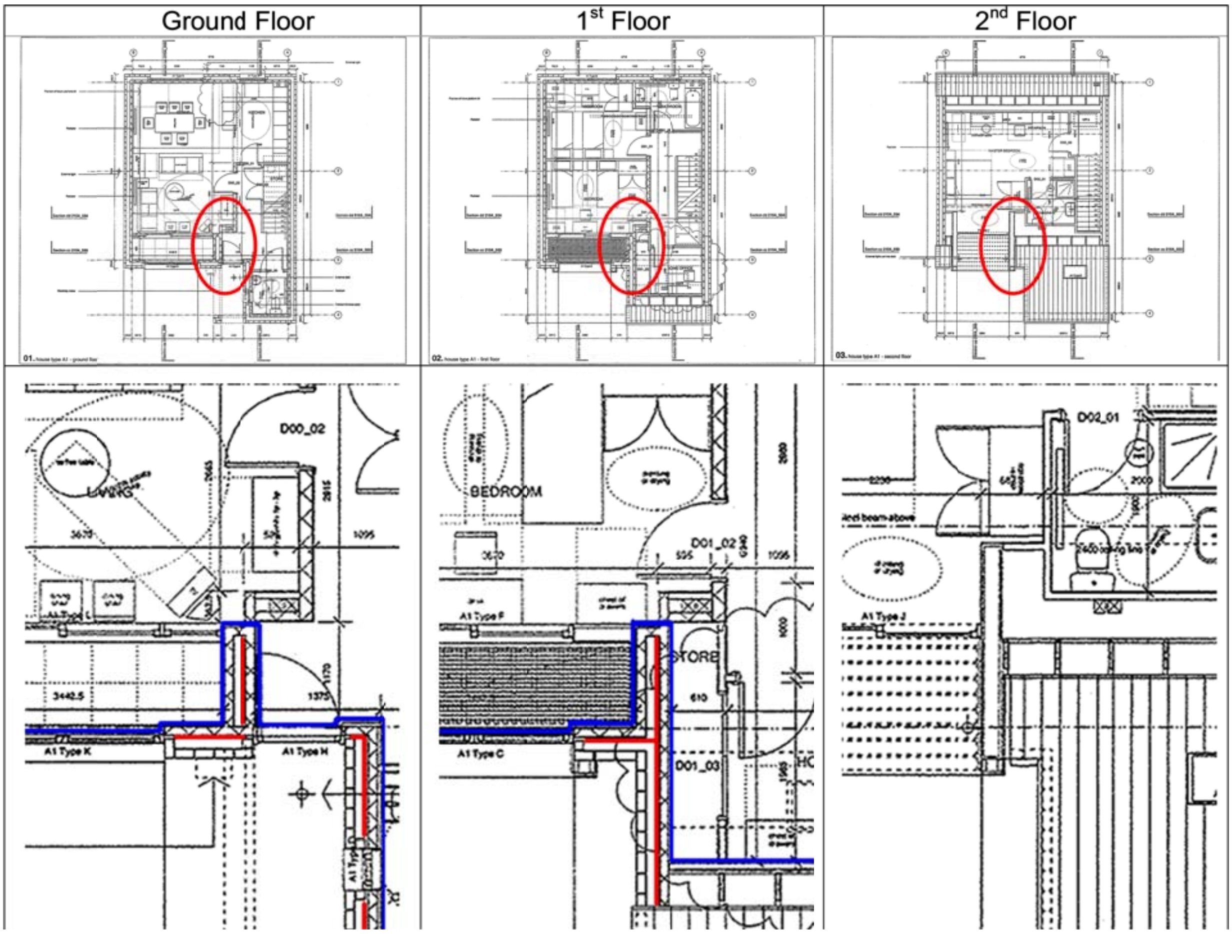

Figure 1 Potential thermal bypass in the A1 prototype (from the architects' drawing 2154_100).

10 Other problem details required a lot more involvement and some of the issues were not fully appreciated until the details were part constructed. An example of a problematic detail was the canopy above the front door on both dwellings illustrated in Figure 2.

a) A1 (masonry) prototype – The drawings (2154_779) raised issues regarding thermal bridging, sequencing (buildability), and a potential condensation risk with the air barrier on the cold side of the insulation. The sections shown in the drawings do not cover the corners and junctions, where particular difficulties arose. Figure 2 shows the underside of the canopy with the thermal bridge from the intermediate floor directly through the steelwork to the supporting pillar. Insulating the small gaps between joists and walls and between the metal webs of the joists to prevent further bridging was deemed problematic so an on-site decision was made to underdraw the whole canopy with polyurethane foam insulation taped to the external wall insulation on all 4 sides, thus reducing any bridging through joists and steelwork. Sealing the gaps around the metal web joists to make them more airtight was done with expanding foam, but some air movement between the external wall cavity and floor void appeared inevitable. Installing an airtightness membrane under floorboards which linked up to the 2 parallel internal parged blockwork walls of the downstairs WC and the home office cupboard as well as the 2 walls at the eaves and door head exposed design and sequencing problems not detailed on the drawings, the membrane also had to be punctured to allow rainfall collected during construction to drain.

b) A2 (SIPs) prototype – The drawings again appeared to position the air barrier and VCL the wrong way around and a problem along the downstairs WC side of the canopy, this resulted in an uninsulated void with a potential thermal bridge. Without any mineral wool on site the void was filled with expanding foam; this had the additional benefit of increasing the airtightness of the joint between the insulated floor above the canopy and the intermediate floor above the ground floor toilet. A piece of polyethylene DPM over the canopy, with silicone sealant around the edges, before covering over with the flooring board was chosen to provide the link between the air barrier at the wall and that in the canopy. The VCL was stapled to the underside of the canopy after it was filled with insulation and boarded. A decision was made on site to lay a double bed of sealant on top of the beams around the perimeter of the canopy, and then lay the membrane on this, before placing the floorboards over the membrane. This solution should prove to be airtight, but by leaving the edges uncut, so that they can be folded and taped around the edges, provides robustness to the solution.

The as-built drawings may well represent some of the changes to design that occurred on site, but it is unlikely that all the sequencing issues will be covered in the design details, particularly those involving membrane and insulation installation.

Figure 2 Front canopies in the A1 and A2 prototypes during construction.

11 Other details which presented difficulties not highlighted in the original designs included:

a) The architects appeared to have attempted to minimise penetrations through the air barrier and building fabric; a principle not adhered to so rigorously by the services designers. A number of these penetrations appeared to be ad hoc decisions made by the installers and not through design. The installers regularly appeared to bear little regard for the integrity of the airtightness barrier and thermal performance.

b) The positioning of boiler flues and consumer units positioned away from their "preferred" locations in the prototype dwellings as a result of the Secured by Design compliance. Although this problem may be peculiar to the prototypes and may not occur when either of these dwellings are replicated.

c) There were additional issues regarding the design of the M&E systems. The displacement of insulation by MVHR ducting and soil and vent pipes in the masonry prototype was commonplace; this was not an issue in the SIPs prototype where all ducting either ran through the floor voids or through boxed in internal voids.

d) Membranes were included in many design drawings in plan and section, but little or no instruction was supplied as to how to maintain continuity at corners, junctions, penetrations, openings and other complex details. The dormer window detail epitomized this, the architects constructed models to increase their understanding of this detail and held a meeting at Leeds Met to help resolve many of the issues, but a considerable amount of on-site design and modification was still necessary.

e) The use of expanding foam to fill and cement construction gaps was prevalent on site, but barely mentioned in the design. In some cases, it was also used instead of insulation; drawing 2154_722 which shows the window sill detail with a strip of insulation beneath the sill board annotated in the drawing only as "insulation", this could be interpreted as any kind of insulation by the contractor - expanding foam was used.

12 A number of design issues were specific to the A1 prototype and the thin joint masonry construction process:

a) Continuity of the airtightness membrane in the sloping roof sections around trusses, purlins and internal partitioning proved very difficult to achieve; instructions on how this should be done were not always apparent in the design. Drawings in section and plan did not fully appreciate some of the difficulties encountered at many of the 3D junctions.

b) There appeared to be a lack of definition of which particular tapes and sealants were to be used in the specification. Tapes which required additional compression or mechanical fixings were specified in instances where no such additional support was present. There were problems with adhesion to the lightweight blocks. The air barrier membrane manufacturer's multi-purpose tape was specified for sealing the roof airtightness membrane to the numerous different plastic, metallic, wooden and ceramic materials rather than a selection of substrate specific adhesive tapes and sealants.

c) The installation of the PU-filled PVC-U cavity closers (drawing 2154_700) created difficulties in trimming back the cavity wall insulation to fit flush to the closers which were installed after the external brickwork had been completed. A sequence change to install the closers prior to the brickwork would have assisted this or the site manager's preference would have been to allow the wall insulation board to continue across to the edge of the opening. In both instances it would have been possible to then seal the insulation to the blockwork to prevent air movement around the insulation boards at openings.

d) A late design modification made during construction involved raising the roof by 1 brick course. As some of the wall insulation had already been cut at the eaves, adjustments were needed, which appeared to involve filling gaps with expanding foam.

13 Design issues specific to the A2 prototype and SIPs system:

a) The timing of the completed working drawings for the A2 prototype was such that construction had already commenced prior to publication. Panel drawings were understandably not produced by the manufacturer until receipt of a confirmed order; this was always going to be an issue because the prototypes were constructed on such a short timescale.

b) With no airtightness membrane on the inside of the panels, continuity of the air barrier relied on silicone sealant linking the OSB boards on the internal faces of the SIPs panels. As no gasket material was specified between the panels the same sealant was also used for this purpose. It appeared in many areas that this sealing only occurred on the peripheral edges, whereas a designed-in gasket would have sealed throughout the entire depth of the wall, this was particularly apparent at the most narrow gaps where difficulties were encountered injecting sealant deep into the structure.

c) The trimmer joist in the 1st floor to allow for the lifetime homes future lift access was omitted from the manufacturer's working drawings and had to be subsequently re-introduced.

d) The detail at the sole plate and slab perimeter assumed the 20mm insulation lining the internal face of the external wall panels was extended down to the base of the slab. As the slab had to be laid before the wall panels were erected this was impossible to achieve, with the insulation, at best, only able to run down as far as the top of the slab.

Construction observations

14 Site observations commenced in July 2009 and were undertaken throughout the construction period. Visits were planned wherever possible to permit observation of key details. Over 20 site visits were made between August and October 2009 to ensure that little was missed by the research team. At each site visit, the research team took photographs to maintain a record of the construction, talked to site operatives to clarify what was being witnessed and why, and discussed observations with the site manager.

15 The site manager was very well informed and extremely helpful to the research team, regularly questioning what he was being asked to do and considering whether there was a better way to do it and often acting as an arbitrator between various concerned parties. Site observations by the research team were always discussed initially with the site manager to either substantiate or moderate their concerns. Any suggestions prompted by the research team were initially proposed to the site manager to attain his opinion on their practicability.

16 The slab perimeter insulation below floor level in both prototype dwellings presented some difficulties (Figure 3). In both dwellings there were issues relating to fitting insulation around the underfloor vents at the front and rear of the properties, with gaps remaining around the vents and the vents displacing insulation. In the A1 prototype, the partial fill insulation was subject to mortar build-up and damage resulted in additional discontinuities of the insulation layer and gaps between the inner leaf and insulation boards. In the A2 prototype, the full fill rigid board insulation allowed air gaps between the insulation and inner leaf, all the joints were taped but some gaps between insulation boards remained, and often the insulation was trimmed short of the top of the slab creating a thermal bridge through the floor slab directly underneath the sole plate.

Figure 3 Perimeter insulation below floor level in the masonry prototype, and at various stages on the SIPs prototype.

A1 (masonry) construction issues

17 The blockwork sub-contractor foreman had not used the thin joint masonry construction method before, so it was as much a learning process for him as for the rest of the site staff. He appeared to rely heavily on the one particular block-layer who was familiar with the techniques involved.

18 The mortar scoop was adapted to provide mortar at the edges of perpends and bedding layers (Figure 4) after comments that the joints didn't look full because there was no excess mortar at the edges that required striking off. Additional work was created in removing the excess mortar with an abrasive tool prior to both applying the wall insulation externally and the parge layer internally. Using the abrasive plate, rather than just striking off, removed the powdery surface layer which had caused a problem with tape adhesion to un-parged blockwork; instead it left a dusty residue on the blockwork which presented new adhesion problems.

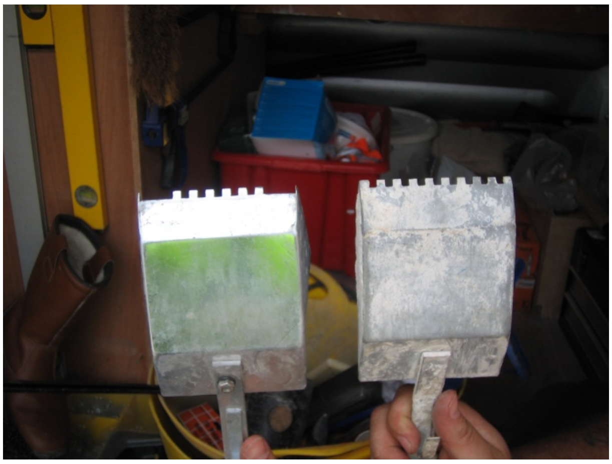

Figure 4 The adapted mortar scoop, on the left, with the 2 outer teeth removed from each side.

19 All the joist ends for both timber joists and RSJs penetrating through the blockwork were covered with a breathable polyethylene tanking strip on the outer surface of the blockwork using double-sided butyl tape and stapled through the tape prior to the insulation going on. This appeared to rely on the insulation board applying enough pressure to hold the tanking strip against the blockwork and butyl tape to ensure airtightness. Leakage detection with smoke puffers under pressurisation showed leakage around the RSJs in the attic even though the tanking strip had been applied and the insulation mechanically fixed. This problem was foreseen by the research team and discussed with the site manager; alternative options were suggested, including wet-applied bitumastic materials, but the taped membrane solution was used as originally specified.

20 Generally the wall insulation appeared to be fixed impressively; the polymeric retaining clips were extremely quick and easy to use, as were the helical wall-ties, according to the subcontractor using them. The fixing method for the retaining clips was to drill a 10mm pilot hole, push in the outer part of the clip, then tap the inner pin in. This method allowed full 1.2 x 2.4m sheets to be used on the walls, increasing speed of installation and reducing the number of joints between boards compared to standard sized cavity insulation boards. All the joints between the insulation boards were taped using a metallic tape which bonded well to the clean metallic faces of the insulation boards, but not so securely to the exposed foam on the board perimeters.

21 Concerns were raised in September 2009 when numerous cracks began to appear in the thin joint blockwork (Figure 5). These cracks were generally at/near the centre of walls, at/near the centre of sills, under padstones and at the internal angles of corners. When the block manufacturer was approached over the cracking in the blockwork this response was received from the Development Manager of the block manufacturer:

"*None of these cracks showed displacement to the block face, and are typical of drying shrinkage associated with cementitious materials. Although it is not possible to give a complete guarantee against drying shrinkage, we had instructed our Recommended Contractor to include bed joint reinforcement in alternate courses, and this has contributed to controlling the drying shrinkage in this instance.*

This type of cracking is not of a structural concern. However, we were also asked to consider the affect on air tightness through the construction: As far as the fine cracking is concerned, the effect will be negligible. For the slightly wider cracks, we would have advised raking out and applying a suitable sealant prior to dry lining. However, on this occasion we understand the walls are to be parged before finishing, in which case no further action need be taken."

Figure 5 Cracking of the blocks in the masonry prototype.

22 The membrane above lounge front windows which formed the air barrier between the frame and the intermediate floor was originally made up on site using strips of a stiff dpm-type membrane, as this was material readily available on site and had also been used to wrap around the exposed edge of the intermediate floor at the sunspace. Using materials already present on site is a common construction practice to attempt to save time and money but in this case it resulted in the membrane having to be removed and replaced with a more suitable material at a later date.

23 A detail which caused considerable additional time and effort was maintaining continuity of the airtightness roof membrane, with numerous problems being encountered.

a) The use of trussed rafters meant that it was not possible to fix large uninterrupted areas of the air barrier membrane as shown in the sectional drawings; instead there were numerous time-consuming cuts, joints and folds involved in working around the roof trusses.

b) The lengths of membrane that were laid over the steel purlins and at intermediate floors often had inadequate laps/flanges to allow the roof membrane to be jointed to them. The same problem arose around timbers installed for the partition knee walls on the 1st and 2nd floors. On different occasions these strips were either omitted in error, inadequately fitted, unsuitable, or the relevant operative was not aware that any membrane was required through a lack of communication.

c) Working around internal partition walls and other 1st fix installations increased complexity due to sequencing difficulties. This was compounded when repairs to the air barrier were necessary and access proved a major difficulty.

d) The taping of the joints in the membrane proved to be problematic. Where there was nothing firm or solid behind the membrane, only mineral wool insulation or a void, the tape often appeared to have gaps where it has not been pressed down firmly enough on initial application or had subsequently come away. The act of applying enough pressure often resulted in small rips occurring where the membrane had been stapled to the rafters. The insulation installers performed much of the initial taping using their standard tape. A great deal of re-taping with more suitable adhesive tapes and other reparatory work had to be performed as the installers tape proved inadequate.

e) Fixing the membrane to the unparged blockwork presented difficulties, although if the intended build sequence of parging all the external walls much earlier in the construction had been followed this would have been substantially reduced.

f) Some of the sequencing issues were themselves a result of these buildings being prototypes and subject to a more stringent testing regime. It was not until the first site meeting on 15th July that it was agreed to review the programme to include airtightness testing while the air barrier was still accessible and perform pre and post parging tests to assess the effectiveness of the parging layer. The repercussion of these late changes was that some of the first fix installations had already occurred prior to parging and certain areas of blockwork remained unparged. Unfortunately some of the soil pipes and MVHR ducting had been installed in corners where cracks in the blockwork had appeared, with pipes and ducts fitted close to the walls (and in some cases already boxed in); these prevented access to apply the parging right into these corners and a number of these cracks remained unsealed.

A2 (SIPs) construction issues

24 There were a number of issues regarding the detailing at the slab perimeter and sole plate including levelling and grouting of the sole plate, slab perimeter insulation performance and insulation continuity, and fixing and linking of various membranes. Figure 6 shows the variation between the as-built and as-designed detail, the gap illustrated beneath the sole plate in the as-built detail being filled with an injectable grout.

a) The SIPs sytem manufaturer's BBA certificate indicates that there should be an injectable grout between the sole plate and slab where spacers/shims are required to level the soleplate, the designs showed no gap between the sole plate and slab so no such grout appeared on the design. The main contractors were responsible for grouting the gap between the sole pate and floor and received details of the recommended material from the SIPs system manufacturer. This gap varied from 0 to >30mm in places. The grouting was delayed until after 20mm internal insulation had been installed, making job much more difficult to perform successfully.

b) The insulation between the slab perimeter blockwork and dpm was a 10mm thick expanded polystyrene expansion strip rather than the 20mm rigid PU foam specified was laid prior to the wall panels being erected. As the bottom of the 20mm internal insulation did not extend right down to the slab level (in some cases there were a 20 to 30mm gaps) there was a discontinuity in insulation around most of the slab perimeter to varying extents. This was exacerbated by gaps between the full-fill perimeter insulation boards and at the top of the slab perimeter insulation in the external wall cavity as shown in Figure 3.

c) The underfloor membrane was wrapped up over the edge of the soleplate and fixed to the outer sheathing of the panels using butyl tape and a staple gun; this process involved removing the breather membrane from the external face of the wall panels and re-fixing it over the top of the returned dpm. A problem remained at thresholds where the soleplate was cut out to make the level thresholds; this was patched up with additional tape, membrane and sealant.

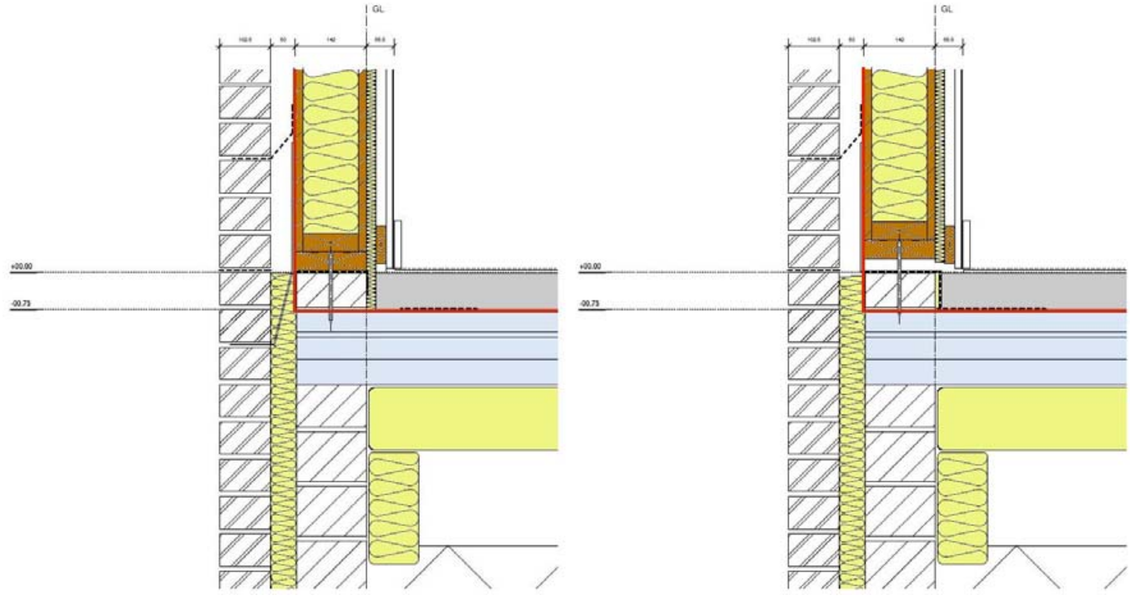

Figure 6 Adapted from drawing 2154_820, a comparison between the as-designed (left) and as-constructed (right) sole plate detail.

25 In the centre of the floor slab the area around the penetration for the soil pipe, between the hall and lounge, formed its own small area between foundation walls. This was omitted when the rest of the slab was laid and the penetrations not sealed around at the most appropriate time, it remained unfilled until after the sole plate had been positioned.

26 The panel erection occurred throughout August 2009. Solid timber connectors were joined using a bead of expanding foam along the recessed side of the connection immediately prior to fixing the panel in position to achieve an airtight connection at this junction, allowing potential for gaps where the foam bead was not laid properly or as the panels were adjusted into their final positions before

mechanically fixing. The standard corner detail observed on site was a nailed butt joint using silicone sealant/adhesive rather than a proprietary gasket at the junction.

27 The SIPs panel erectors were aware of gaps between and around the wall panels which had been observed by the Leeds Met researchers (Figure 7), and indeed other, similar ones which had not been remarked upon. This was regarded as normal by them and part of their standard process was to inspect for these gaps and make them good with mastic, adhesive and foam, as they deemed appropriate, as construction progressed and before they were covered over with the breather membrane externally or with subsequent construction and/or insulation internally. Whether these gaps were completely filled or just sealed at the surface was not determined, and questions remain about the longevity of such repairs.

Figure 7 Gaps observed between SIPs panels during construction were sealed using a silicone mastic as construction progressed.

28 In their apparent haste to unload a lorry the contractors were observed lifting all the panels at once, rather than just in discrete packages, a few at a time (Figure 8). This resulted in damage to the panels where the lifting straps from the crane were positioned. The contractors again said they would be made good on site with OSB cut-offs, silicone and expanding foam where necessary.

Figure 8 Unloading of the SIPs panels and the resulting damaged panel.

Fabric performance testing

Airtightness testing

29 Airtightness tests were conducted by Leeds Met, in accordance with ATTMA TS1 (ATTMA, 2007), at a number of similar stages on each prototype dwelling, the results of these tests are listed in Table 1 and summarised below. External contractors were used to perform pressurisation tests on the prototypes for compliance purposes at the end of November 2009.

a) Tests were conducted prior to air barrier completion to identify areas of concern and allow for remedial works to be undertaken. In the A1 (masonry) prototype this involved testing both immediately before and immediately after application of the internal parge coat.

b) Further tests were undertaken on air barrier completion (19/11/2009), to provide an indication of the final level of airtightness whilst the air barrier was still accessible should additional remedial work be necessary. In the case of the masonry prototype, substantial additional sealing of the roof membrane was carried out following this, to reduce the air leakage through the roof membrane, before a final result was obtained for compliance purposes by the external pressurisation testers.

c) Pressure tests were performed on each dwelling prior to the coheating tests commencing. This was representative of the completed construction stage at which compliance testing was performed.

d) Final pressurisation tests were conducted immediately following the coheating tests. This allowed an accurate calculation of heat loss through ventilation for the duration of the coheating tests, with an added benefit of showing where the accelerated drying, shrinkage and settlement caused by the coheating tests may have affected the airtightness of the dwellings.

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	
A1 (masonry) 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
A2 (SIPs) Prototype	25/09/2009	3.33	3.30	3.32	3.06	
	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

30 In the initial test (19/10/09) on the masonry prototype a mean air permeability of 5.87 $m^3/(h.m^2)$@50Pa was achieved. The majority of the air leakage appeared to be around, through and between the air barrier membranes in the sloping roof sections. The air tightness at this detail appeared to deteriorate as the test and subsequent leakage detection progressed; the failure of some of the adhesive tape used indicating that it was clearly not suitable for this purpose. In fact, the test, itself, had to be halted and restarted to allow the replacement of the air barrier, with a more suitable material, above the ground floor doors into the sunspace (Figure 9). Further air leakage paths identified included:

- At the ground floor wall junction, particularly at the room corners.
- At electrical penetrations through the blockwork and airtightness membrane.

- Through settlement cracks in the blocks themselves.
- Where built-in joists penetrated the blockwork, particularly RSJs.
- Where the tape used to seal around the windows had lost adhesion to the blockwork.
- Around and through the rooflights.
- Between some of the individual glazing elements that made up the patio doors.
- Through closed trickle vents.
- At numerous points around the balcony.

Although leakage detection revealed air leakage at all the above details, it should be stressed that the most concerning air leakage detected appeared to be through and around the air barrier membrane used throughout the sections of sloping ceiling. Inaccessible areas and awkward junctions were often areas where leakage appeared most severe, and the black gaffer tape used by the insulation fitters was already coming away from the membrane in several places. The physical act of performing the pressurisation tests appeared to be beyond the adhesive limits of this tape and was causing it to fail at pressure differentials of 50~60 Pascal.

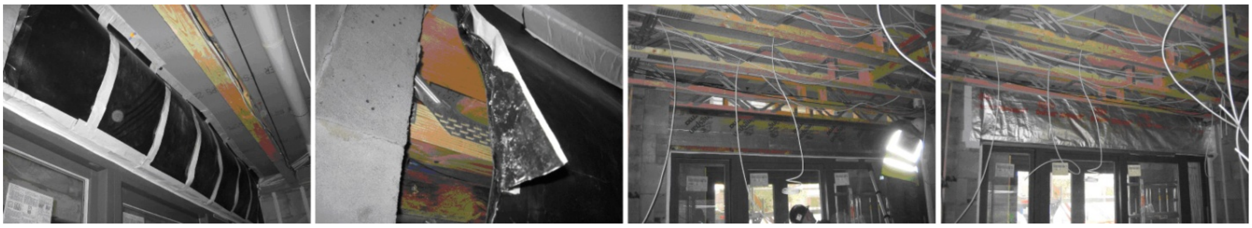

Figure 9 The original membrane in the A1 prototype between the lounge and sunspace, shown failing during the pressure test, being removed and a replacement installed.

31 A 2nd test on the masonry prototype (22/10/09) was conducted 3 days later and achieved a mean permeability of 5.56 $m^3/(h.m^2)$@50Pa. The major difference in the dwelling from the previous test was that the inner face of the blockwork of the external walls had been lined with a parging coat which seemingly resulted in a disappointing improvement of only 0.31 $m^3/(h.m^2)$. However, further deterioration in the adhesion of some of the tape used to seal the airtight membrane was identified. In particular, the silver duct tape used to connect the membrane around the balcony to the woodwork had come away, most noticeably where the moisture content of the wooden sheeting appeared higher, and the black gaffer tape used to connect the air barrier in the sloping ceiling had failed in many places along joints in the membrane in the 2nd floor and attic. Leakage that was previously observed through cracks in the blockwork had been eliminated by the parging layer. However, the parging layer was not complete, with areas of exposed blockwork at intermediate floor voids, behind services and boxing, at window reveals and in other inaccessible areas such as those behind trusses, partition walls and in the small void between the balcony cheek and gable wall.

32 It is difficult to say how effective the parging coat was in reducing the airtightness of the masonry prototype, as this was not the only variable between the pre and post parging pressurisation tests. Quantifying the changes in air leakage due to the absence of the parge coat in some of the more critical areas and the effect of the deterioration in the membrane fixings is impossible. However, if a sequence of construction in which no 1st fix installations were allowed before the parge coat was complete was strictly adhered to, it is anticipated that the improvement observed would have been greater. It is considered likely that the parged blockwork surfaces would make better substrates for taping window frames and membranes to than was encountered using the adopted build sequence.

33 The test on the masonry prototype at air barrier completion (19/11/09) was conducted under very gusty wind conditions; the excessive wind speeds made the result obtained 4.33 $m^3/(h.m^2)$@50Pa, indicative only. Leakage detection showed air leakage in many of the same locations as previously observed but reduced rates of leakage was perceived, attributable to construction progression and application of additional sealing. As detected air leakage through details which had not changed (e.g. trickle vents) appeared to perform worse, it was assumed this was due to improvements elsewhere. The most significant improvement was found where additional sealing had been carried out on the airtightness membrane in the attic. More suitable tapes had been used and a great deal of effort had been applied to repair around penetrations and other discontinuities. Additional leakage paths were also detected where penetrations had been made into service risers for waste pipes in the bathroom and kitchen; these would be hidden behind kitchen units and the bath panel and no attempt had been made to repair the damage caused (Figure 10).

Figure 10 Air leakage into the service risers under dwelling pressurisation in the A1 prototype – 19/11/09.

34 The pre-coheating pressurisation test of the masonry dwelling on 04/01/10 showed a further increase in airtightness to 3.98 $m^3/(h.m^2)$@50 Pa; this appeared to be due to decoration and some fairly intensive secondary sealing measures. Thermal imaging under dwelling depressurisation revealed significant air leakage into the intermediate floor void above the front door head and canopy which had not been possible to detect previously because there had been no temperature differential between inside and out. The coheating test was performed throughout January 2010 with the internal temperatures held at 25°C for 4 weeks, causing accelerated drying and shrinkage throughout the dwelling. Immediately following the coheating test the dwelling was re-tested and gave a result of 4.17 $m^3/(h.m^2)$@50Pa, a slight decrease in airtightness of 0.2 $m^3/(h.m^2)$ and approaching the figure obtained prior to the additional secondary sealing being carried out.

35 In the initial test (25/09/09) on the SIPs prototype a mean air permeability of 3.32 $m^3/(h.m^2)$@50Pa was achieved. At the time of the test the air barrier of the dwelling (considered to be the inner OSB leaves of the wall and roof panels) was complete and had been lined with a further 20mm of insulation, so was no longer directly accessible should remedial action have been necessary. Leakage detection revealed that most of the air leakage observed was at junctions between different building elements and at openings. Using smoke puffers, the main points of air leakage identified were:

- The ground floor perimeter, particularly noticeable at the front patio door threshold.
- Doors and windows, the tape used to maintain air barrier continuity often only joined the window/door frames only to the breather membrane not to the wall panels.
- Around and through the rooflights.
- Between some of the individual glazing elements that made up the patio doors.
- Around electrical penetrations through the external walls.
- At numerous points around the balcony, particularly at the small void between the balcony dormer cheek and the gable wall.
- In the attic, through gaps in the sealant around the ridge beam and at isolated points between the roof panels.

Generally, these points of air leakage appear very similar to those observed for the masonry prototype, and by and large seemed to be at a similar level of severity with the exceptions that the masonry prototype had increased air leakage in the attic, through the sections of sloping roof and through the trickle vents which were not present in the SIPs prototype..

36 The pressurisation test at air barrier completion (19/11/09) on the SIPs prototype showed an improvement in airtightness, with a mean air permeability of 2.41 $m^3/(h.m^2)$@50Pa. Much of this improvement was considered to be associated with the finishing of details at the window and door jambs, heads and sills, although the front patio door threshold was still unfinished and appeared to be possibly the worst performing detail under leakage detection. The leakage paths observed previously were still apparent, but additional secondary sealing had reduced the severity of many of them. After completion of the test, it was discovered that the balcony door was closed but not locked shut with the door fully pressed against the seals; a subsequent spot-measurement was taken with the balcony door fully closed giving a result of 2.33 $m^3/(h.m^2)$@50 Pa (2.15 h^{-1} air leakage rate).

37 The test performed on the SIPS dwelling before the coheating test on 04/01/10 benefited from internal decoration and finishing and showed a further increase in airtightness to 2.21 $m^3/(h.m^2)$@50 Pa. However, when the house was tested immediately following the coheating test, on 04/02/10, a mean air permeability result of 2.42 $m^3/(h.m^2)$@50Pa was recorded, the same value as achieved at air barrier completion stage. This can be attributed to the accelerated shrinkage, drying and settlement caused by the coheating test.

Coheating tests

38 Coheating testing of both prototypes took place simultaneously between 04/01/10 and 04/02/10. The procedure followed that described in the original project proposal. Initial pressurisations tests were carried out on 04/01/10 and the dwellings were heated up gently until 07/01/10 when all the equipment had been installed and was fully operational. Usable data was collected from 09/01/10 and continued until the test was completed on 04/02/10 and the final pressurisation tests were performed. Although the research team requested that access to the houses during this period was limited to emergencies only, there were days when the clients required access to both properties and the data for these days was compromised. All of the available data has been included in the figures provided below, but may be removed from the final analysis should the effects of these interventions prove significant.

39 A reliable comparison between the measured and predicted heat loss depends on the accuracy of both the measured and the predicted data. The predicted heat loss figures used in the analysis are based on those supplied by the architects, listed in Table 2; air permeability results were taken from compliance testing and in the SIPs prototype the damaged ground floor patio door, 1st floor bedroom and front door windows were accounted for by increasing the predicted heat loss by an arbitrary 6 W/K. Uncertainty remains over some of the predicted figures, including the ~5% difference in heat loss areas between the 2 dwellings and the variations in the values measured for air permeability at the start of the coheating tests compared to the official test results.

Table 2 Predicted Heat Loss – Fabric values extracted from the architects' SAP worksheets dated 10th December 2009.

	A1 - Thin-Joint Masonry			**A2 - SIPs**		
Element	**Area**	**U-Value**	**Heat Loss**	**Area**	**U-Value**	**Heat Loss**
	m^2	W/m^{2}K	W/K	m^2	W/m^{2}K	W/K
Window Type 1	12.22	0.961	11.74	12.22	0.961	11.74
Window Type 2	17.24	1.272	21.93	15.24	1.263	19.25
Window - Broken			0.00			6.00
Rooflight	3.00	0.960	2.88	3.00	0.960	2.88
Door	2.30	1.000	2.30	2.30	1.000	2.30
Ground Floor	50.31	0.155	7.80	51.34	0.155	7.96
Canopy Floor	2.00	0.120	0.24	3.37	0.170	0.57
Canopy Floor Type 2			0.00	5.00	0.130	0.65
Wall Type 1	163.89	0.170	27.86	189.51	0.150	28.43
Wall Type 2	12.12	0.150	1.82			0.00
Wall Type 3	0.98	0.190	0.19			0.00
Roof Type 1	75.40	0.155	11.69	74.14	0.150	11.12
Roof Type 2	2.00	0.180	0.36			0.00
Totals	**341.46**		**88.80**	**358.12**		**90.90**
Thermal Bridging using Y	*341.46*	*0.030*	*10.24*	*358.12*	*0.030*	*10.74*
Calculated thermal bridging			**13.66**			**14.32**
Total Fabric Heat Loss			**102.463**			**105.220**
Permeability	3.20	m^3/(h.m^2)@50Pa		2.20	m^3/(h.m^2)@50Pa	
Sheltering Factor	1.00			1.00		
Background Ventilation Rate	0.16			0.11		
Volume	407.30	m^3		411.13	m^3	
Ventilation Loss			**21.51**			**14.92**
Fabric			102.46			105.22
Ventilation			21.51			14.92
Total			**123.97**			**120.14**

40 Each dwelling was heated to 25 °C over the test period using electrical resistance heaters with circulation fans used to mix the internal air to ensure a uniform temperature was achieved throughout the dwellings. The heat loss in W/K was determined by measuring the daily electrical energy used to maintain the internal temperature relative to the daily mean difference between the internal and external temperature (ΔT). The total energy used by all the equipment (not only the resistance heaters, but circulation fans and data-logging equipment) was included in the calculations of energy utilised to maintain the internal temperature. Solar gains, using actual solar insolence combined with a calculated solar aperture were included. The mean daily values recorded over the coheating test period are listed in Table 3. Periodic releases of CO_2 into the dwellings allowed the actual ventilation rate during the coheating tests to be calculated from the concentration decay. During the final 2 weeks of the tests heat flux sensors were placed strategically within the dwellings to allow actual physical U-values at a number of locations to be calculated from direct measurements of heat flow through the building fabrics.

Table 3 Mean daily measured values over the period 11-Jan-10 to 03-Feb-10 with solar corrected mean daily power and heat loss values.

	A1 Prototype – Thin Joint Masonry	**A2 Prototype – SIPs**
Power Input (W)	3062.0	2745.2
Mean Insolation (W/m^2)	43.0	43.0
Wind Speed (ms^{-1})	1.23	1.23
ΔT (K)	21.5	21.8
Raw Heat Loss (W/K)	143.2	126.5
Solar Corrected Power (W)	3213.4	2899.0
Solar Corrected Heat Loss (W/K)	149.5	132.9

41 Figure 11 charts the solar-corrected daily total power consumption (in Watts) required to maintain the 25 °C internal temperature at the range of internal/external daily average temperature differentials experienced. Assuming no energy input is required when ΔT = 0 the gradient of the line of best fit through these points (shown on the graph) provides the measured heat loss coefficient, this is plotted alongside the predicted heat loss from Table 2. Figure 12 shows the comparable data for the A2 prototype. Using this method, the measured data provide a heat loss coefficient of 149.5 W/K for the A1 prototype with an R^2 correlation of 0.367, and a heat loss coefficient of 132.9 W/K for the A2 prototype with an R^2 correlation of 0.511. The lower correlation of results observed for the masonry prototype is likely due to wind effects, which affected the masonry prototype to a greater extent than the SIPs prototype due to its higher air permeability.

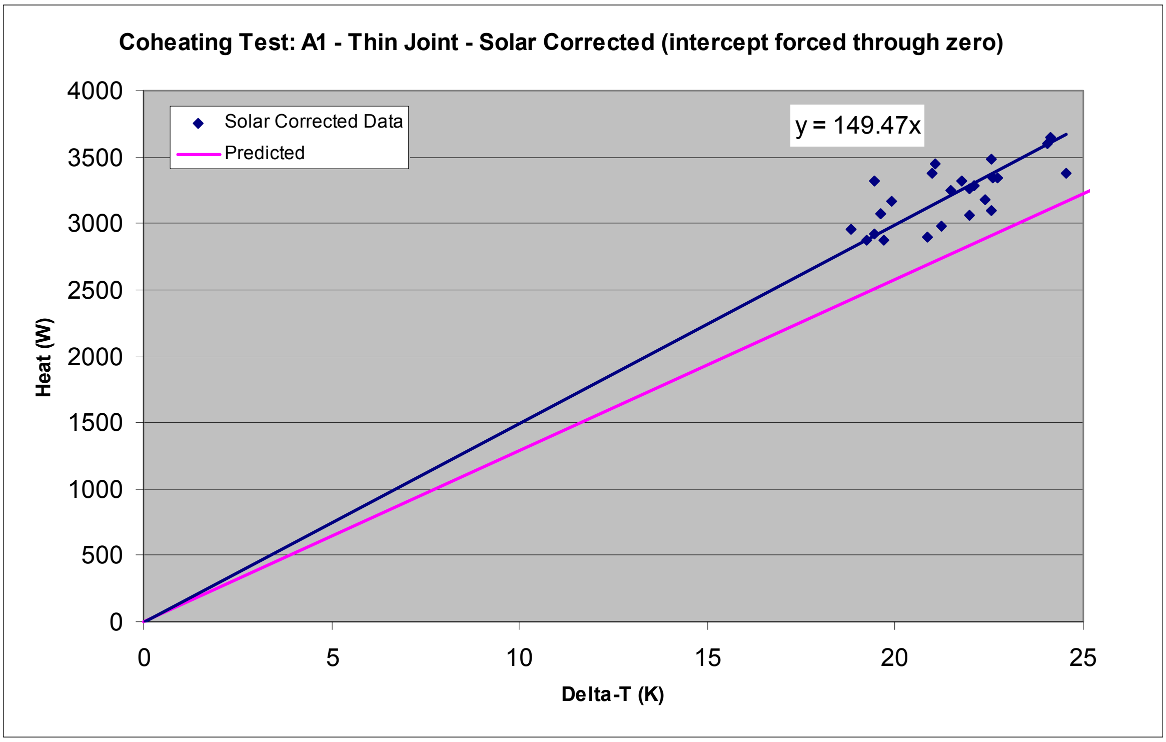

Figure 11 Masonry Prototype – Measured versus predicted heat loss performance.

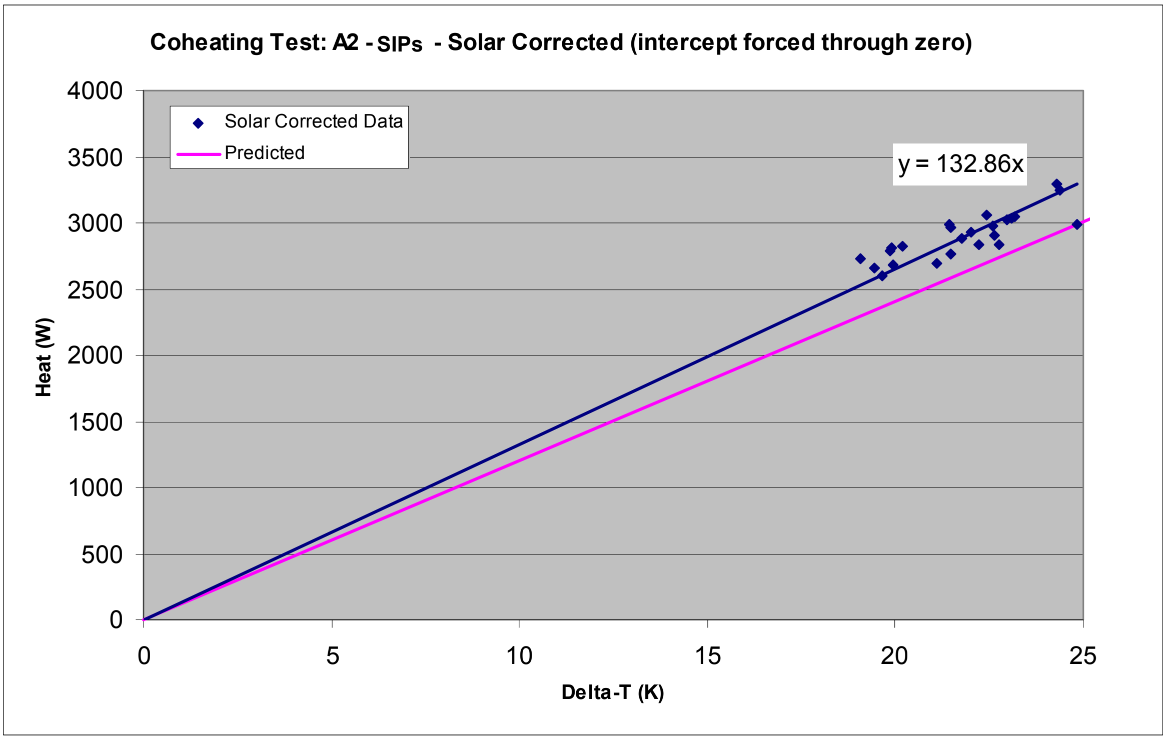

Figure 12 SIPs Prototype – Measured versus predicted heat loss performance.

42 A summary of these data, including the heat loss parameter values, is displayed in Table 4. The figures for heat loss parameter being calculated using the floor areas listed by the architects in the draft SAP worksheets used to obtain the predicted heat loss values,151.76 m^2 for the masonry prototype and 154.50 m^2 for the SIPs prototype.

Table 4 A comparison of predicted and measured fabric performance

	A1 Prototype - Masonry		A2 Prototype - SIPs	
	Heat loss coefficient	**Heat loss parameter**	**Heat loss coefficient**	**Heat loss parameter**
	W/K	W/m^{2}K	W/K	W/m^{2}K
Predicted	123.97	0.83	120.14	0.78
Measured	149.47	0.98	132.86	0.86
Variation	+ 25.50 (20.5%)	+ 0.15 (18.1%)	+ 12.72 (10.6%)	+ 0.08 (10.3%)

43 The 25.50 W/K difference between predicted and measured heat loss coefficients in the masonry prototype represents a 20.5% increase over the design value, for SIPs prototype the 12.72 W/K difference denotes a 10.6% increase. These increases over design values are due to a number of factors. There may be inaccuracies in the calculated predicted values which affect the size of the variation[1], but the majority of the underperformance is more likely due to the as-built details and elements not achieving their specified design performance, an increase in ventilation heat loss over the course of the test, construction faults and modifications, and possible design and process issues. Additional measurements taken during the coheating tests assist the estimation of the extent of some of these issues; airtightness issues were shown up by pressurisation tests before and after the coheating test and through the use of CO_2 as a tracer gas during the tests, and degradation of fabric U-values was investigated by measuring heat flux through elements of the fabric to measure the actual effective U-values at given points using heat flux sensors.

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[1] Increasing the predicted ventilation heat loss in the A1 prototype by using the air permeability tests performed before and after the coheating test instead of the compliance test figure would have increased the total predicted heat loss by 5~6 W/K, using the target air permeability of 3 m3/(h.m2)@50PA would have reduced the total predicted heat loss by ~1 W/K.

44 To put the results into context, the prototypes increased heat loss over predicted performance from the prototype dwellings is shown alongside other dwellings tested by the Leeds Met research team in Figure 13. The prototype dwellings are shown in red. The size of the differences detailed in Table 4 may be of concern, but they are amongst the lowest differences recorded by the Leeds Met research team in coheating tests on new build dwellings. As detached houses the prototypes were not affected by underestimated heat losses from separating walls as observed in the other tested dwellings. In fact, A1 prototype emerged as the closest to design values yet tested by the research team for a masonry dwelling and the A2 prototype was on a par with the best performing timber framed new build houses.

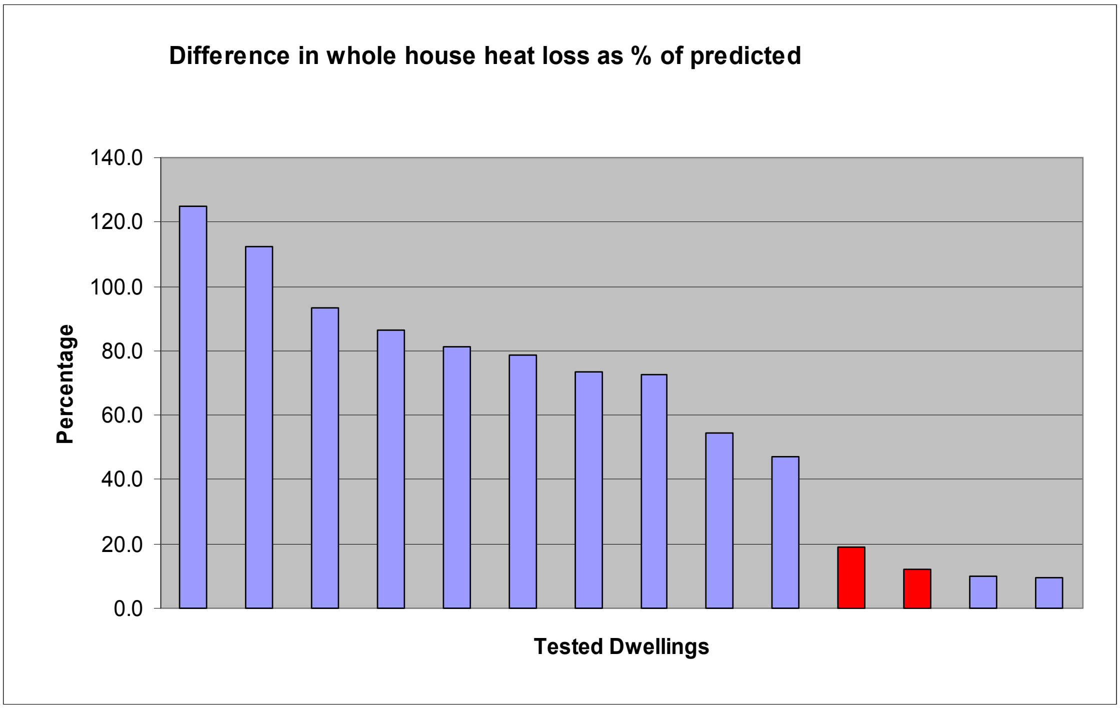


Figure 13 Variation between predicted and measured results in new build dwellings from coheating tests performed by Leeds Met since December 2005.

45 Using a ventilation heat loss value derived from the measured air permeability (the mean value of tests performed at the start and end of the coheating tests) to re-calculate the predicted heat loss of the dwellings allows the variation from designed performance to more accurately represent the thermal performance of the fabric by removing some of the variations caused by air leakage. These revised values are shown in Table 5. Figure 14 illustrated these revised values in context with other dwellings and highlights the high level of performance against two award winning projects, the client's own Elm Tree Mews development (Bell, Wingfield, Miles-Shenton and Seavers, 2010) and the Stuart Milne Group's prototype Sigma Home (Stevenson and Rijal, 2008) which was built on the BRE's Innovation Park in 2007 using a MMC closed-panel timber frame system with designed elemental U-values comparable to the Temple Avenue prototypes.

Table 5 A comparison of predicted and measured fabric performance using measured air permeability values.

	A1 Prototype - Masonry		**A2 Prototype - SIPs**	
	Heat loss coefficient	**Heat loss parameter**	**Heat loss coefficient**	**Heat loss parameter**
	W/K	W/m^{2}K	W/K	W/m^{2}K
Predicted	129.30	0.85	120.20	0.78
Measured	149.47	0.98	132.86	0.86
Variation	+ 20.17 (15.6%)	+ 0.13 (15.3%)	+ 12.66 (10.5%)	+ 0.08 (10.3%)

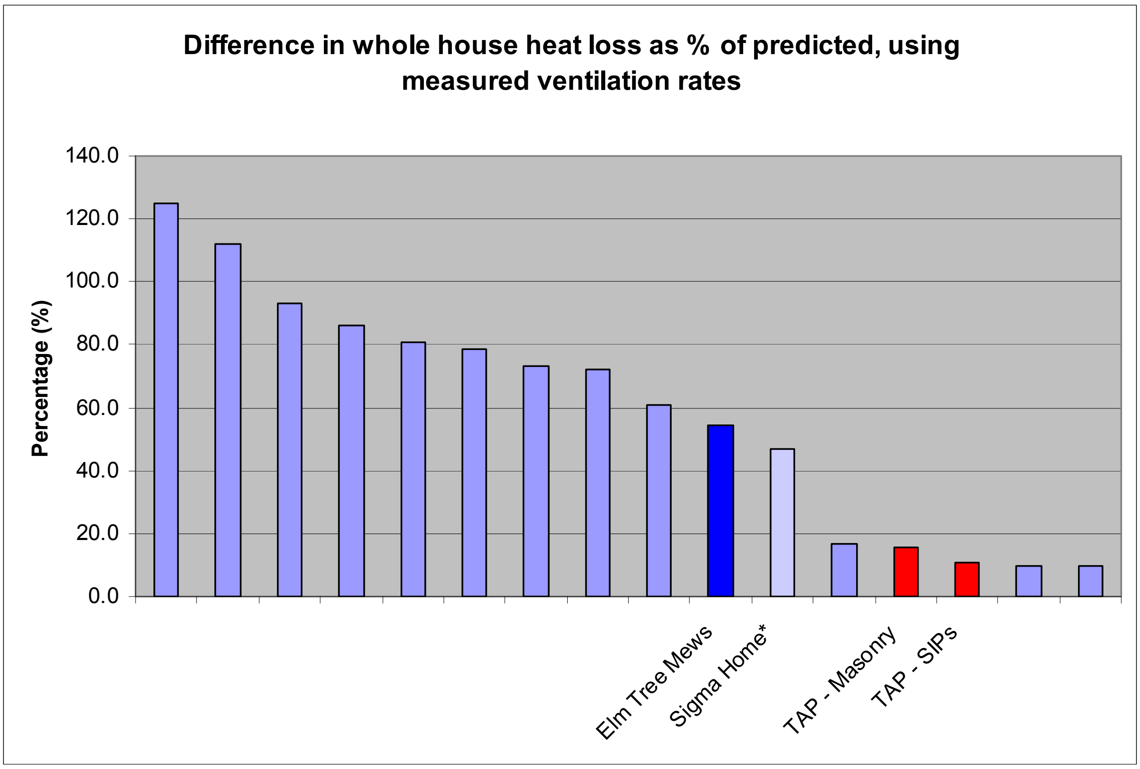


Figure 14 Variation between predicted and measured results using measured ventilation rates.

46 The internal temperatures recorded in the dwellings throughout the coheating tests are illustrated in Figure 15. They show the heat-up phase from 07/01/10 and a levelling off of internal temperatures occurring very quickly to allow useable data to be collected from 09/01/10. The unheated attic spaces remained relatively constant at 22 °C in the masonry prototype and 20 °C in the SIPs prototype, even when additional heaters and controllers were added on 20/01/10 to even out the variations in temperature within the dwellings. The series of temperature peaks observed between 28/01/10 and 01/01/10 were due to long periods of unbroken sunshine causing some overshooting of temperatures in rooms on the southern elevation. However, this provided a good variation to allow more accurate solar correction of the measured data. The variation in daily average temperature differential required for producing reliable trends from the recorded data was achieved; daily average external temperatures ranged from -2.5°C (09/01/10) to 4.9°C (27/01/10) over the test period. Figure 16 shows the total power consumption of the prototypes over each 10 minute interval throughout the coheating test period. The increased solar gains over the period 28/01/10 to 01/02/10, and consequential peaks in external temperature, can be clearly seen by the decreased electricity demand for heating during daylight hours.

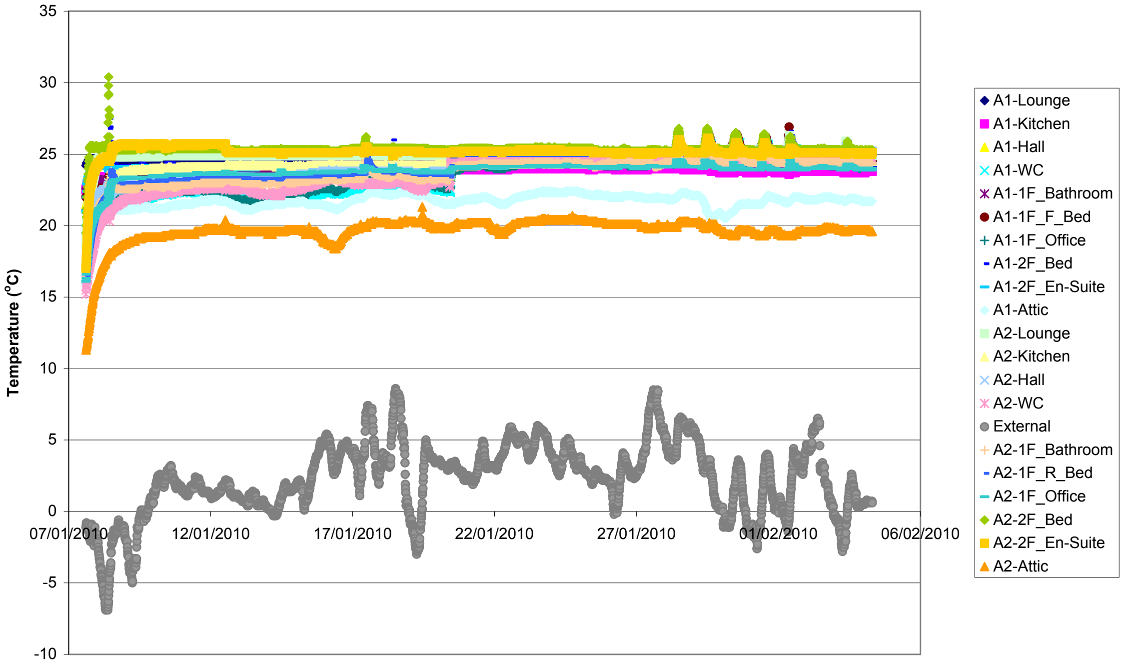


Figure 15 Temperatures recorded in the prototype dwellings over the coheating test (10 minute data).

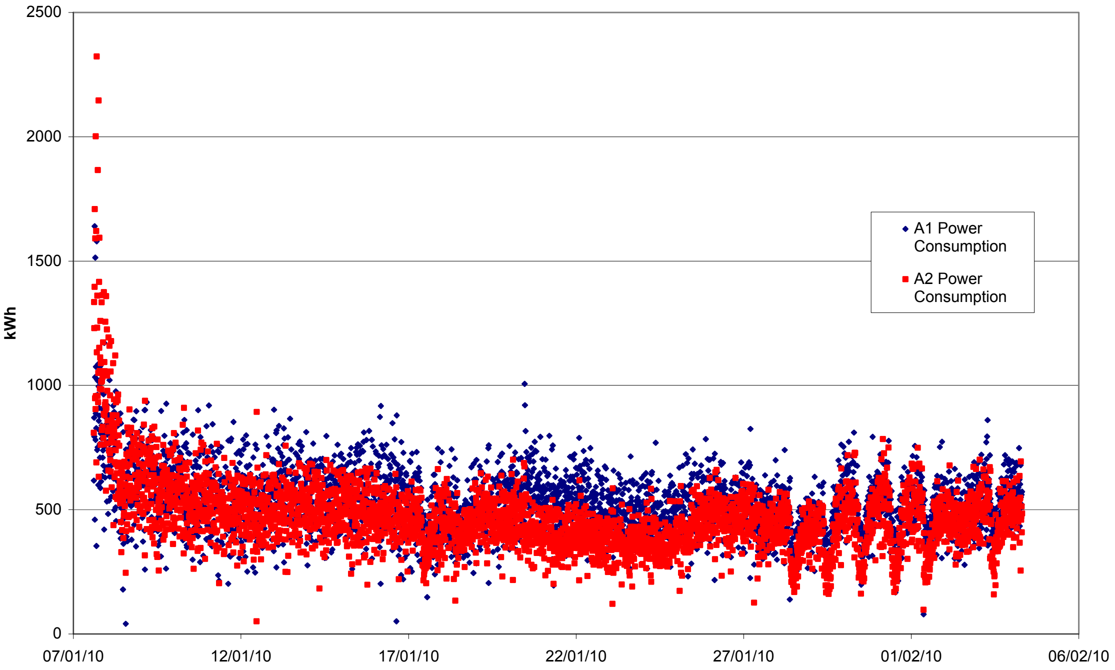
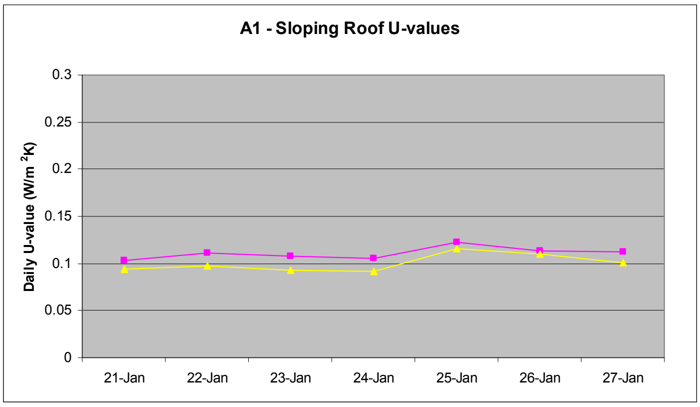
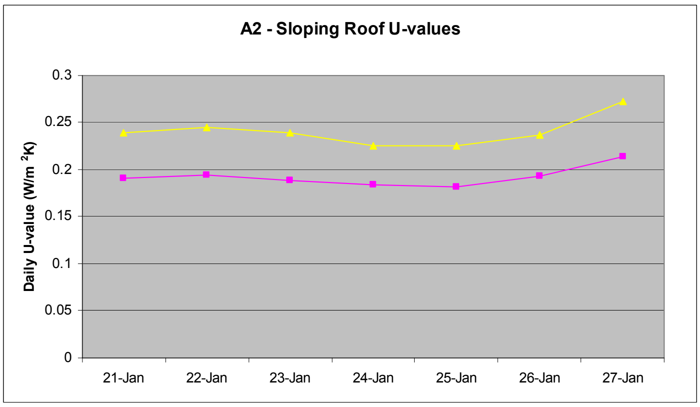
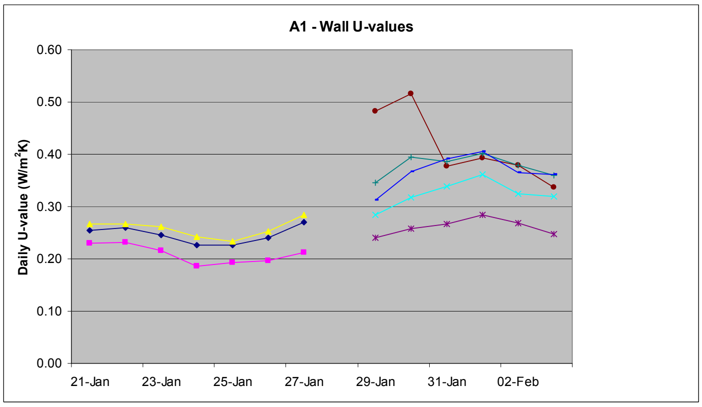
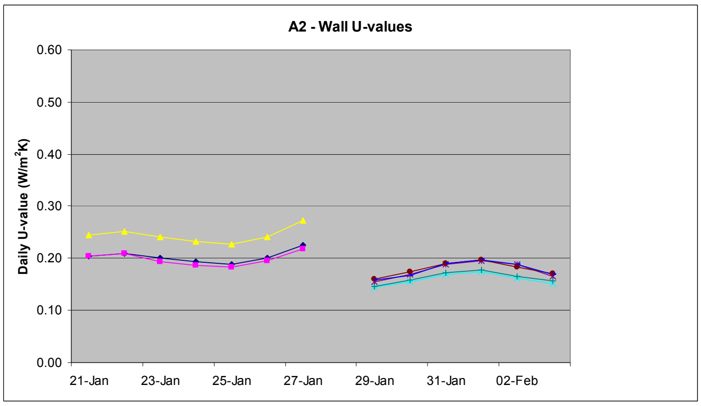


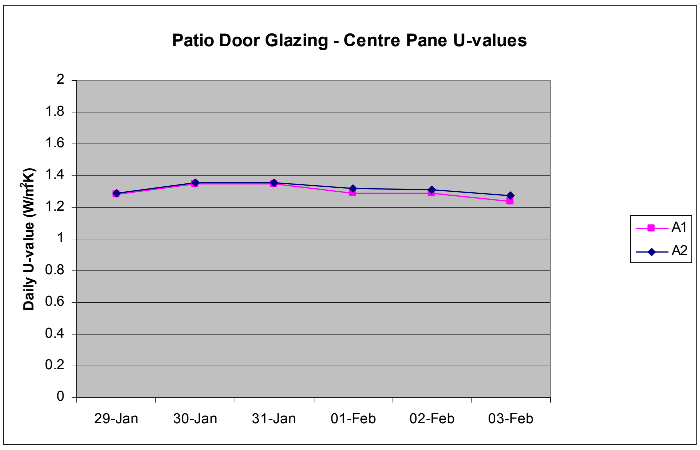
Figure 16 Total '10 minute' power consumption in each prototype over the coheating test.

Heat flux measurements

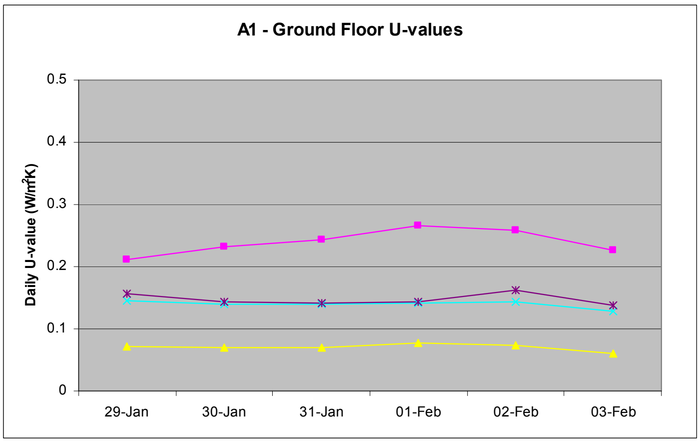
47 To measure actual U-values being experienced, and try to explain some of the differences between design and measured heat loss, Hukseflux heat flux sensors were placed in select locations in both dwellings between 21st January and 3rd February. These were sited on the 2nd floor East-facing gable wall and the North-facing sloping ceiling in the A1 prototype and their 1st floor equivalents in the A2 prototype until 28th January, and then moved to the vertical 1st floor North facades, the North-facing lounge windows and the ground floors in the lounges in both dwellings for the remainder of the coheating tests. Table 6 charts the daily average U-values derived from the heat flux at these points and comments on the results achieved.

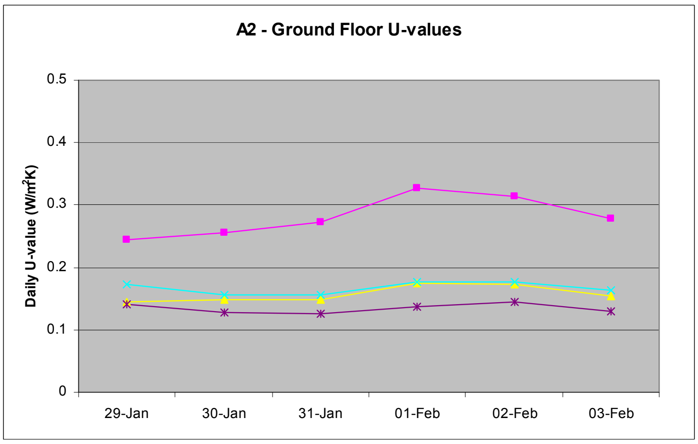
Table 6 Daily average U-values derived from the heat flux measurements.

Derived daily U-values	**Comment**
	Measured U-values of the sloping roof sections varied considerably between the 2 prototypes. Table 2 lists similar predicted U-values of 0.155 and 0.15 W/m^{2}K for the sloping roof in the A1 and A2 prototypes respectively however what was measured varied significantly from these forecasts. The airtightness tests in the A1 prototype revealed sizeable air movement in the sloping roof section. This might lead to some heat recovery through bulk air movement, lowering the measured U-values but it is unlikely that this will account for the entire discrepancy from design value observed. The proximity of structural timber could be adversely affecting the measured U-values in the A2 prototype. However, with limited time and resources, and no possibility of deconstruction we can only surmise on the cause of these inconsistencies.
	
	The measured U-values for the A1 prototype's gable wall varied from ~0.2 to 0.3 W/m^{2}K and were marginally greater than those recorded for the A2 prototype. However, when the heat flux sensors were relocated to the north façade, by the side of the rear bedroom window there was a significant rise in U-value and a greater range was identified, particularly on the 29th and 30th of January when the weather was windier. The measured U-values for the A2 prototype north facade were slightly better than those determined for the A2 gable wall, a range of 0.15 to 0.2 W/m^{2}K for the north facade against 0.2 to 0.25 W/m^{2}K for the gable wall. This variation may have been related to the proximity of a timber stud to the sensors on the gable wall but the U-values were generally much higher than the nominal 0.15 W/m^{2}K quoted by the architect
	



The measured U-values for the glazing provided by the high-performance double-glazed windows proved to be remarkably consistent, with both prototypes providing centre pane U-values of ~1.3 W/m^{2}K.





The floor U-values varied considerably with proximity to the external wall, but were very consistent between the 2 dwellings.

The highest values (~0.3 Wm^{2}K) were recorded for the sensor in each house closest to the external wall-floor junction, with the A1 prototype outperforming the A2 by 10~20% closest to the slab perimeter. The other sensors away from the wall junction ranged from ~0.08 to 0.18 W/m^{2}K.

Preliminary calculations provide an average U-value of around 0.15 W/m^{2}K for the floors, which is consistent with the nominal calculated U-value for the floor used by the architects (0.16 W/m^{2}K).

49 In the case of the wall on the north façade of the masonry prototype, there are some significant discrepancies in measured U-values. The worst measured heat flux densities were recorded on the windiest days suggesting some bypassing due to air movement arising from the edges of the boards by the window reveal, this was supported by photographs taken during the construction and thermal imaging (Figure 17). The measured U-values of 0.25 to 0.52 W/m^{2}K on the North facing wall were drastically higher than the measured U-values on the gable wall of 0.19 to 0.28 W/m^{2}K , a wall with no window openings, and all were higher than the design U-value of 0.17 W/m^{2}K, listed in Table 2. In the SIPs prototype U-vales between 0.18 and 0.27 W/m^{2}K were measured on the gable wall, but lower values between 0.15 to 0.20 W/m^{2}K on the North façade, where in both cases the design value was 0.15 W/m^{2}K. These figures would suggest that rather than portraying an average U-value of the walls, the design U-values listed in Table 2 represent a 'best-case' or minimum U-value for these elements.

Figure 17 The masonry prototype 1st floor rear wall (North façade), showing gaps in the insulation, heat flux sensor placement, and thermal image captured during coheating.

Tracer gas ventilation rate measurements

50 Throughout the coheating test daily, bursts of CO_2 were released into the dwellings and the CO_2 concentrations recorded on both the ground and 1st floors (Figure 18) in order to calculate the ventilation rate. The subsequent rates of decay allowed air change rates to be determined based on the period of time taken for the CO_2 concentration to return to the background levels (Roulet and Foradini, 2002).

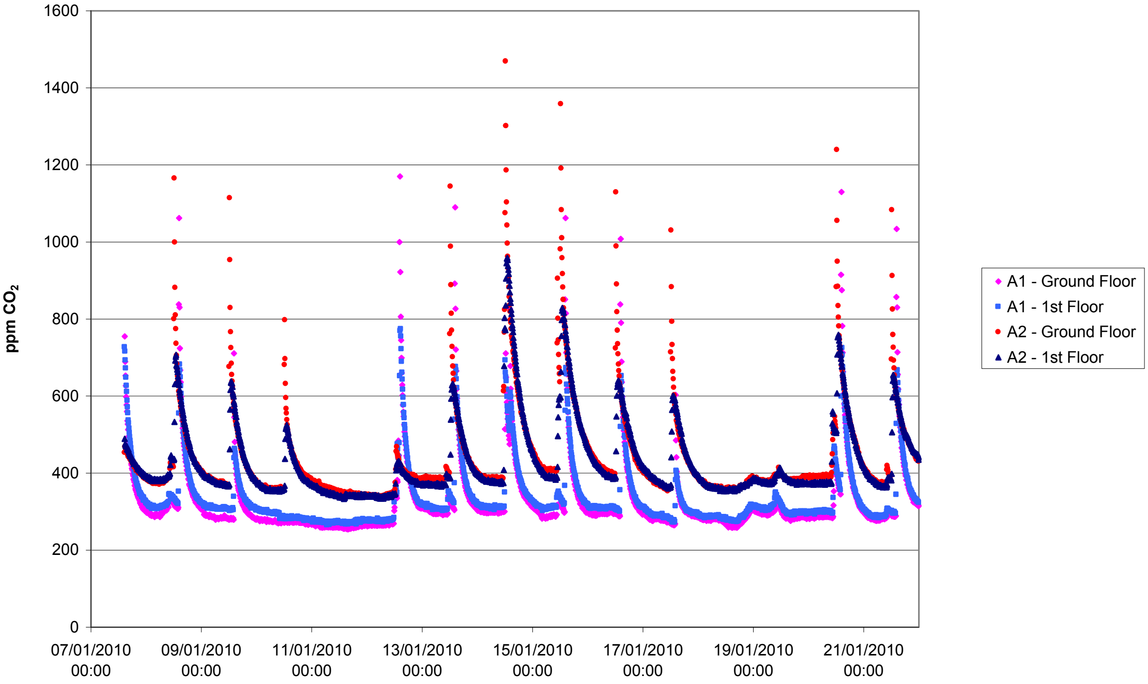


Figure 18 Levels of CO_2 recorded in the 2 prototype dwellings (10 minute data).

51 The air change rates calculated for the A1 prototype varied from 0.32 to 0.42 h^{-1} on the ground floor and 0.31 to 0.41 h^{-1} on the first floor over the test period, in the A2 prototypes they were 0.21 to 0.28 h^{-1} on the ground floor and 0.16 to 0.24 h^{-1} on the first floor. No pattern of change over time was observed in either property, the variations appearing to be more consistent with changes in wind speed and direction, although this has yet to be fully analysed. That the air change rates varied little over the test period supports the pressurisation test data showing no significant change

in air leakage rates between pressure tests undertaken at the start and finish of the coheating tests, where the results of 3.5 ~ 3.7 h^{-1} for the A1 prototype and 2.0 ~ 2.2 h^{-1} for the A2 were measured at an induced pressure difference of 50 Pascal. The variation in measured background CO_2 levels of between 70 and 100 ppm is somewhat harder to explain and after due checking was confirmed as not down to instrument error. The background CO_2 concentrations observed in the A2 prototype were much more representative of environmental levels suggesting other factors at work in the thin-joint house. The variation will have been due in part to the variation in relative humidity in the dwellings, shown in Figure 19, where the mean RH readings for the ground and 1st floors were some 7 to 10% higher in the A1 prototype, but whether this can account for such large variations in concentration is difficult to determine; there may be some adsorption of the CO_2 by moisture contained within the building fabric or by the structure itself..

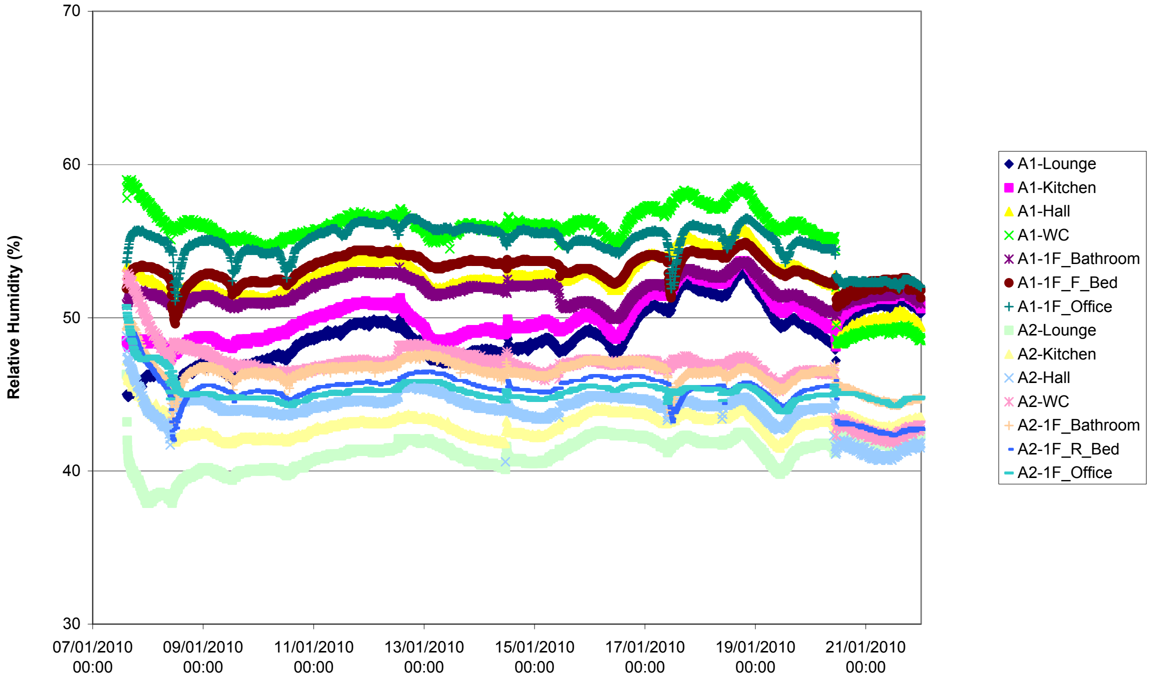


Figure 19 Relative humidity readings in ground and 1st floors of the 2 prototype dwellings (10 minute data).

Services

52 Without in-use or simulated in-use measurement any evaluation of services performance is limited in its scope; however, it was possible to measure basic flow rates in the ventilation system and to observe, where possible, its design, installation and commissioning. Some of the issues relating to design and installation have already been discussed, this brief section highlights not only additional problems specific to this system but also issues relevant to the commissioning of services in general and the inconsistencies that arise. Recent reports by the LeedsMet research team have observed, measured and commented on issues of non-correspondence between post-construction commissioned performance and in-use systems performance in greater detail at Elm Tree Mews (Bell, Wingfield, Miles-Shenton and Seavers, 2010) and the Stamford Brook Field Trial (Wingfield, Bell, Miles-Shenton, South and Lowe, 2008).

Mechanical ventilation (MVHR) system

53 The MVHR Engineer deemed the concealed terminal roof tiles originally built into the roofs of the prototypes inadequate and insisted that terminal vents with a greater capacity were required (Figure 20). On the SIPs prototype the replacement terminal vent was installed in an alternative location on the opposite side of the roof due to accessibility and related safety issues, these safety issues also meant that the original vented roof tile was left in position but not connected.

Figure 20 The replacement “mushroom-type” terminal vent, complete with lead slate fixing, and the originally-fitted “concealed” vent tile removed from the masonry prototype.

54 The MVHR ducting displaced insulation between the rafters in a number of instances in the masonry prototype, with the ducts laid close to rafters there were areas with no mineral wool insulation around the ducts and increased potential for air movement within the rafter void, the result being an envisaged deterioration in the thermal performance of the roof structure. Additionally, positioning the ducts in this void meant that additional penetrations through the air barrier were required, necessitating added complexity in sealing the membrane and ensuring its continuity, with extra joints and associated taping increasing the likelihood of defects. Installing the ductwork out of sequence also resulted in discontinuities in the parging layer in this dwelling, with its associated airtightness issues.

55 The MVHR system was installed and commissioned by the manufacturer, with commissioning certificates issued on 9th December 2009. Immediately following the coheating tests the research team took measurements of air flows at the supply and extract grilles in both houses and as there were discrepancies between the air flows measured and those stated on the certificates the manufacturer was requested to re-commission the systems. Questions were also raised about whether the whole house extract and supply rates had been balanced, primarily for energy efficiency purposes, and also over the effectiveness of the boost on supply rates. This led to the manufacturer re-commissioning both systems and issuing revised certificates on 16th February 2010. Additional flow measurements taken by the research team on 24th February and 2nd March 2010 indicated that the claimed supply rates were still not being achieved in the A1 prototype and neither system was balanced. The manufacturer was called back to site on 9th March to meet representatives of the client, the research team, the M&E specifier and the main contractor. When the systems were re-examined and the manufacturer agreed that problems with both systems persisted. Representatives from both the manufacturer and the M&E specifier met on site again on 23rd March and the systems were finally fully commissioned to a standard acceptable by the M&E specifier, a third set of commissioning certificates was expected in due course. This raises serious questions over the commissioning process, and without the independent checks being carried out by the research team the MVHR systems in both prototypes would not have been providing either the energy efficiency assumed in the design calculations or even the trickle supply and boost extraction warranted by Part F of the Building Regulations.

Conclusions and recommendations

56 A number of the issues raised in this report are due to the fact that these buildings were prototype dwellings and constructed over a fairly tight schedule. The project was a learning process and

modifications to the designs as construction progressed were to be expected. As such, a full set of detailed design drawings was not available at the start of the project, this should not be the case on replication.

57 The prototypes were built on a site with 1 site manger concentrating on just 2 properties with numerous formal and informal site inspections performed by contractors, consultants, architects and specifiers, clients and other building professionals and interested parties. Such micro-managing and intensive quality control is not expected with replication on a much larger scale; this should be reflected in any performance estimates and expectations.

Design

58 Constant contact between the designers and contractors, and all other concerned parties, was possible throughout the prototype build process and can be regarded as one success of the project. However, these discussions are expected to be of a more limited nature in any subsequent construction and many of the ensuing issues are likely to be resolved by decisions made on site or through the procurement process and not verified by the designers. This is particularly the case where specific performance criteria of the specified products are paramount.

59 Ideally the detailed drawings should also include those of services to help eliminate discrepancies between individual sets of drawings supplied to different contractors on site. This could assist in solving certain sequencing issues. In the case of problems like the displacement of insulation by service installers this could also either reduce the number of instances or feed back into the designers’ energy calculations where these were deemed inevitable.

60 Issues relating to process and sequencing should be more prominent in the design, some are simple but easily overlooked (e.g. apply grout under the soleplate before the internal insulation is applied) others require more planning (e.g. fitting of insulation between the joists and walls), particularly where construction needs to be performed “out of sequence” as far as the typical sequence of trades and fixes is concerned. Problems where materials need to be installed prior to access being restricted by additional construction or services should be avoided by including clear process /sequencing notes in the design material.

61 The design and specification of membranes, tapes, adhesives and sealants needs further clarification. The design of membranes at more complex junctions could be adapted to limit the amount of taping and reparatory work by installing dual membranes to avoid patching external corners and at openings. Specifying minimum sizes of laps/overhangs of membranes built in to earlier stages of construction would simplify the process of connecting to them at a later stage.

A1 (Thin-joint masonry) Specific

62 Air movement around the wall insulation boards and between the insulation boards and blockwork did not appear problematic in the drawings, but was observed when the dwelling was tested. The wall insulation was well fitted, but problems persisted at junctions, edges, openings and penetrations. Establishing a way of reducing the air gaps between the insulation boards and walls and finding a suitable edge sealant could significantly reduce this unpredicted heat loss. Maybe the specification of a silicone mastic or adhesive between the blockwork and insulation at the wall perimeters, around openings and at penetrations could assist in reducing this.

63 The trimming back of the wall insulation only to replace it with PU-filled PVC-U cavity closers appeared to be counter productive and contribute to the problems in the previous paragraph. The site manager’s suggestion of just trimming back part of the wall insulation at the jambs so the inner surface of the insulation remained appeared valid.

64 The tanking strip specified at the joist ends appeared to move the air barrier from the internal parging layer to the membrane on the outside of the blockwork wall. A full membrane wrapped around the intermediate floor blockwork courses and linked to the parging layers above and below the intermediate floors would provide a more robust solution but may be impractical to install.

65 The considerable difficulties in maintaining the roof membrane’s integrity around the trussed rafters has not been taken into account on the sectional drawings. One possible solution would be to use an intelligent “breathable” air tightness membrane over the top of the rafters and underneath the rigid board insulation, this could be attached directly to parged internal blockwork surfaces and rooflight frames but difficulties maintaining air barrier continuity at the eaves would persist.

A2 (SIPs) Specific

66 The SIPs system manufacturer’s standard details show two options for jointing wall panels; one as observed on site with the solid timber connector (an engineered connection), the other is usually shown in the literature which has a thin SIPs beam as the connector instead. The latter could make

a significant difference to the timber fraction and reduce the effective wall U-value with no additional design alteration. On site a bead of expanding foam was run along the recessed side of the junction just before fixing the panel to achieve a solid joint between the panels used. This left a potential for gaps if the foam bead was not laid properly or moved when they adjusted the panel into place. A purpose-designed gasket would be preferable solution at this detail if one is available; similarly gaskets would be favoured in many other locations rather than the use of adhesive, mastic and expanding foam observed on site.

67 The continuation of the 20mm internal insulation lining of the external walls down to the base of the floor slab to provide slab perimeter insulation is not buildable due to sequencing issues. The use of 10mm expanded polystyrene expansion strip at the slab perimeter as a suitable substitute needs to be fully assessed, particularly at the front and rear elevations where the underfloor vents replace the full fill insulation boards in the cavity below floor level. Increasing the height of the full fill insulation boards to above the top of the sole plate could mitigate any thermal bridging at this junction, or alternatively review the floor construction process to enable the 20mm perimeter insulation to be successfully installed.

68 No airtightness membrane was specified which occasionally created confusion over whether the air barrier was the inner or outer surface of the wall panels and which surface penetrations should be sealed to. A membrane would add some conceptual clarity to what constituted the air barrier, with everyone aware of its purpose and where any penetrations through it should be sealed.

Construction

69 The restricted size of the site for the prototypes, with limited stocks held on site, meant that some materials were not available at the earliest stages of construction which would be on full-scale production, as a result there were some product substitutions made which would not be envisaged in full scale production. The consequences were the use of expanding foam and mastics being commonplace where more suitable materials were not at hand or readily available and substitute tapes and membranes installed.

A1 (Thin-joint masonry) Specific

70 The scoop adaptation made to provide excess blockwork adhesive on the internal and external surfaces of the blockwork created additional work, in that this had to be removed using an abrasive plate before applying the parging and cavity wall insulation. This seemed to be slightly unnecessary as the parge coat would be filling any gaps on the internal blockwork anyway, but it may have assisted in reducing any gaps between the external face of the blockwork and the wall insulation.

71 Fixing the wall insulation in full sheets proved to be very quick and effective on the large uninterrupted gable walls, with joints between boards minimised and successfully taped. Problems persisted at junctions and linking the wall insulation to the loft insulation, with gaps around rafters and problems with tape adhesion to anything other than the foil coat of the insulation boards.

72 The cracking that appeared in the blockwork is a concern with relation to the airtightness. The pre-parging pressure test revealed air leakage through most of these cracks, if new cracks were to appear post-parging, or existing ones expand, it is possible that new air leakage paths will be created that will be obscured by the dry lining so are not repairable without considerable cost.

73 The unparged block surface presented adhesion problems with the adhesive tapes used. This would not be so much of a problem at openings if the parging layer was complete and returned into the reveals prior to window installation because the window/door frames would then be taped to the paging layer rather than directly to the blockwork, and similarly where the roof membrane needed to be attached to the walls. However, this problem will persist at the tanking strip used on the outer surface of the blockwork at penetrations.

74 Many problems relating to the continuity of the roof membrane are still potentially unresolved and were just worked around on site. Joining the membrane to itself and other substrates, sequencing around floors and partition walls, and dealing with penetrations through the membrane all need designed solutions rather than the on site fixes that were observed.

A2 (SIPs) Specific

75 In these days of laser levels it should be possible for the contractors to fix the sole plated perfectly level, unfortunately variations of up to 30mm in the slab were observed which had to be made up with plastic spacers and an injectable grout. This process was made much more difficult because it was delayed until after the 20mm insulation had been fitted internally.

76 The breather membrane on the outside of the wall panels was returned into the heads, jambs and sills at openings and was not trimmed back prior to window and door installation. What resulted

was that many of the rooflight/window frames were taped to breather membrane in an attempt to achieve an airtight seal rather than to the actual panels, resulting in air leakage at these details. The breather membrane requires trimming back to allow the window frames to be sealed directly to the wall panels to achieve air barrier continuity.

77 A number of wall panels appeared to get damaged as they were unloaded from the delivery vehicle. The contractors installed these panels and then repaired the damaged OSB boards. If there was damage to the inside of the panels, as may well occur if these panels were present on site in larger scale production, clarification is needed on whether or how any repairs would be carried out.

Airtightness

78 The pressurisation test results achieved indicate that the target of 3 $m^3/(h.m^2)$ @ 50Pa is achievable in both forms of construction. Besides the air leakage through the roof membrane and trickle vents in the A1 prototype the houses appeared to perform to a very similar standard, with the masonry prototype appearing to actually perform better than the SIPs around openings and at the ground floor perimeter.

79 Also encouraging was the little reliance on secondary sealing in either dwelling. This was confirmed by the very small deterioration in airtightness over the course of coheating tests, where the accelerated shrinkage and drying caused by the coheating tests had only a minor effect on the airtightness.

80 The pressurisation tests carried out throughout the project emphasise the need to perform such tests at air barrier completion when the air barrier is still accessible and repairs can be implemented and not just to rely on compliance testing on completion. Further clarification of what and where the air barrier is would be helpful; in both dwellings the designs showed the air barrier sometimes as the outer surface and sometimes the inner surface of the inner leaf, if it was defined exclusively as the inner surface, or a particular membrane, this would reduce confusion and aid air barrier inspection. Air barrier awareness could then easily be included in any site induction process.

81 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.

82 The main areas for improvement in the SIPs prototype:

a) 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

b) 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.

c) 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.

Thermal performance

83 Using a comparison of measured vs. predicted heat loss as a measure of the dwellings' fabric performance relies on accuracy of both sets of figures. As the predicted heat loss relies on theoretical performances of materials installed ideally, it is highly unlikely that the predicted performance will be achieved in practice. The results from the coheating tests show that the prototypes are amongst the closest to predicted fabric performance of all the new build dwellings tested by the Leeds Met research team. The coheating test results portrayed as 20.5% above the predicted heat loss coefficient for the masonry prototype and 10.6% above for the SIPs[2] remain a

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[2] The percentage variations is reduced to 15.6% (26.8 W/K) for the masonry prototype if actual, rather than target, air permeability is used to calculated the predicted heat loss; such a change in calculation method would not affect the SIPs prototype variation form predicted value as its measured ventilation rate was significantly closer to the target figure.

concern and further investigation would be required to fully understand why these discrepancies occurred; however, the heat loss parameters of 0.98 W/m^{2}K and 0.86 W/m^{2}K for the masonry and SIPs prototypes respectively are still very low when compared to current UK new build in general.

84 Given the nature of many of the issues observed during the construction and testing periods it is likely that the lessons learnt during construction of the A1 prototype would result in replication of the design outperforming the prototype dwelling and providing fabric performance figures closer to the design values, assuming similar levels of quality control and supervision were maintained. It is questionable whether the same scale of improvement would be possible upon replication of the A2 prototype, where the issues reported on appear to be of less consequence.

85 Heat flux measurements taken during the latter part of the coheating test revealed discrepancies between designed U-values and those derived from the recorded heat flux:

a) Ground floor – The measured values away from the ground floor perimeter were consistent with the design values, but the increased U-values at the slab perimeter reflect the concerns raised from construction observations over continuity of insulation and thermal bridging at this junction. The poorer performance of the SIPs prototype suggests that the excessive bridging around the sole plate/floor junction may warrant additional design consideration.

b) Walls – From the measured values it would appear that the designed U-values of the walls are a minimum rather than the average U-value and the effects of air movement at edges and openings are far greater than predicted 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.

c) Sloping roof – In the SIPs prototype the thermal performance of the sloping roof closely resembled the patterns and values recorded for the external walls. In the masonry prototype the measured U-values were significantly lower than the design values suggesting that the air movement in the voids behind the plasterboard was affecting the measured results, possibly in the form of some heat recovery caused by thermal stack effects promoting air flow upwards through the roof structure.

d) Glazing – The U-values measured closely matched those supplied by the manufacturer and included in the design calculations.

86 Throughout the coheating tests the masonry prototype was affected to a greater extent than the SIPs prototype by variations in wind speed and direction. This was reflected by greater deviations and lower correlations in data collected for heat loss calculations and in-situ U-value measurements. This will have been due in the most part to the poorer airtightness of the dwelling, but may also have been affected by the orientation and greater exposure to some of the more extreme meteorological conditions experienced during the test period, with the masonry prototype more highly exposed to the most severe weather approaching from the North and North East.

87 Temperature peaks between 28/01/10 and 01/02/10 in the rooms with South facing windows provide an indication of the potential for summer overheating. These days experienced long periods of unbroken sunshine and the resultant spikes in room temperature shown in Figure 15 occurred only in rooms with South facing glazing. In some cases the room temperatures were overshooting by ~3 K when the external temperatures were <5 °C; with the thermostatically controlled heaters switching off at temperatures above 25.1 °C this overshoot was due entirely to solar gains. With the coheating tests occurring in January the direct sunlight was able to penetrate further into the rooms and the additional shading which would be provided in the summer by the sunspaces and balcony roofs was circumvented to some extent, but it provides a warning for the likelihood of summer overheating in both construction forms.

Systems performance

88 The debacle surrounding the commissioning of the MVHR system is a serious concern, not just for the ventilation systems but also for the commissioning processes for other services. No client would reasonably assume that information on commissioning certificates was inaccurate, but if independent checks are necessary to confirm the accuracy or validity of claimed system performances then these may be required.

Suggestions for replication

89 A brief list of suggestions for replication is details below, although far from comprehensive these address some of the issues raised in this report and hopefully provide initial ideas on how the performance achieved in the prototype dwellings could be maintained or even improved on replication of the designs.

Drawings:

- Complete sets of drawings, including those for services, should be compared for consistency to avoid design decisions being made on site, particularly those made by services installers.
- Additional sequencing and process details should be included in the design drawings, or find an alternative way of transferring design information to the operatives other than through drawings alone.
- Improved specification of membranes is required, with details of where they may need jointing, folding, lapping and wrapping around some of the more complex details,
- Improved specification of tapes and adhesives is required, ensuring that the correct tapes for the variety of substrates are clearly detailed in the information provided to the relevant trades. Installers need to be made aware of any specific surface preparation that may be required.

Process:

- The level of site supervision witnessed for the prototypes should be maintained on replication if the same quality of construction is to be expected.
- Feedback to the architects needs to be maintained, with a role assigned for somebody with an explicit responsibility to ensure that the designs are carried out to the completion; any on-site modifications and “equal or equivalent” substitutions will need to be ratified by the architects.
- The unspecified use of expanding foam as an airtightness or insulation material should be prevented and specified component, sealants and insulation used.
- If the commissioning of the MVHR system is typical of the commissioning processes of other systems, the performance of services should not be taken at face value.

Thin-joint masonry:

- Trimming back the external wall insulation to replace it with PU-filled PVC-U cavity closers seemed counter-productive when the wall insulation could be bonded to the blockwork during installation to form a better airtight seal around openings and could also continue right up to the window/door frames and negate the need for the cavity closers, saving time and money.
- Air movement between the blockwork and wall insulation could be eradicated by bonding the insulation to the wall, much in the same way as EWI, rather than a total reliance on mechanical fixings.
- The tanking strip used to seal around joist ends could be replaced with a Bituthene or similar self-adhesive type material rather than rely on the butyl tape and compression by the insulation. An alternative to this would be to use suitable joist hangers instead of building in the joists.
- Installation and attempts to maintain continuity of the roof membrane demanded great time and effort in negotiating the roof trusses. This could be significantly reduced by re-designing the roof to avoid the use of trussed rafters or to re-design the air barrier so it would not need to be worked around the trusses, possibly by locating it on the external sides of the rafters.
- The straps used to secure the window/door frames created thermal bridges and difficulties in ensuring airtight junctions at openings which could be significantly reduced by using a box made from plywood, or similar material, which fitted around the opening and was sealed to the structure. The frames could then be secured into this box and sealed around more easily and effectively.

SIPs system:

- The panel jointing could be improved by adopting rebated gaskets, these would provide seals through the entire depth of the wall that would allow for better adjustment of panels and minor repositioning.
- The 20mm additional internal insulation could be repositioned to the outer faces of the external walls. This would have a beneficial effect on the thermal bridging at external corners, internal wall junctions and intermediate floor perimeters.

- An airtightness membrane on the inside of the external walls throughout the entire structure would add conceptual clarity to what constituted the air barrier, particularly at more complex details such as the front door canopy and 2nd floor balcony, and would simplify the sealing of penetrations.
- The need to use plastic spacers/shims and a retro-fitted grout to level and seal beneath the sole plate created both airtightness and thermal bridging issues which could have been avoided if the slab perimeter was level and a gasket system employed. With laser levelling and modern techniques the level of tolerance required for this is achievable; the only remaining question may be whether it would prove cost-prohibitive.
- Window straps again caused problems which would be diminished using a box detail as suggested above for the masonry prototype. This detail would also remove the confusion often observed with sealing window/doorframes to the returned breather membrane at the opening rather than to the structure (or air barrier membrane if installed).

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