'Bridging' the domestic building fabric *'performance gap'*

Abstract

In the UK, it is recognised that there is often a discrepancy between the measured fabric thermal performance of dwellings as-built and the predicted performance of the same dwellings and that the magnitude of this difference in performance can be quite large. This paper presents the results of a number of in-depth building fabric thermal performance tests that were undertaken on three case study dwellings located on two separate Passivhaus developments in the UK; one masonry cavity and the other two timber-frame. The results from the tests revealed that all of the case study dwellings tested performed very close to that predicted. This is in contrast with other work that has been undertaken regarding the performance of the building fabric, which indicates that a very wide range of performance exists in new build dwellings in the UK, and that the difference between the measured and predicted fabric performance can be greater than 100%. Despite the small non-random size of the sample, the results suggest that careful design coupled with the implementation of appropriate quality control systems, such as those required to attain Passivhaus Certification, may be conducive to delivering dwellings that begin to *'bridge the gap'* between measured and predicted fabric performance.

Keywords

Air tightness, building performance, housing, thermal barrier, coheating, heat flux.

1 Context

Over a number of years, it has become evident that there is often a discrepancy between the predicted energy and thermal performance of a building and the measured performance of that building in-use. This discrepancy is often referred to as the *'performance gap'*. The *'performance gap'* affects domestic and non-domestic buildings and is a problem of international significance. Studies undertaken in the UK (Bordass, Cohen, Standeven & Leaman, 2001 and Zero Carbon Hub, 2010), in Sweden (Bagge & Johansoon , 2013), across Europe, Japan, the USA and Canada (Thomsen, Schultz, & Poel, 2005), in Germany (Galvin, 2014), in Italy (Tronchin & Fabbri, 2008) and in Belgium (Hens, Janssens, Depraetere, Carmeliet & Lecompte, 2007) have revealed discrepancies between the measured and predicted energy and thermal performance of whole buildings, or individual building elements. The reasons identified for the discrepancies in performance tend to be widespread and highly context specific. Despite this, they can be broadly categorised into three main areas - those relating to the thermal performance of the building fabric, those relating to the energy performance of the building services and those relating to occupancy. It is also important to recognise that all three of these areas are also influenced by the external environmental conditions.

This paper is concerned with the thermal performance of the building fabric in new UK dwellings only. Despite this, the findings from this paper are likely to be equally applicable to other building types both within the UK and abroad.

2 Introduction

In the UK, there is mounting evidence that the measured energy and thermal performance of dwellings as-built can be significantly worse than that predicted (Zero Carbon Hub, 2010 and 2014; Carbon Trust, 2011). In some cases, differences between the measured and the predicted performance of dwellings of more than 100% have been documented (Stafford, Bell & Gorse, 2012; Zero Carbon Hub, 2010). As there are over 27 million dwellings in the UK (Palmer & Cooper, 2013) accounting for just under 30% of the UK's total CO_2 emissions (DECC, 2013), such large differences between the measured and the predicted performance of dwellings have the potential to seriously undermine the UK Government's desire to mitigate the effects of climate change and achieve the desired 80% reduction in national CO_2 emissions by 2050 based on 1990 levels (HMSO, 2008).

In response to this issue the Zero Carbon Hub (ZCH), having previously reviewed the available evidence on the *'performance gap'* (see Zero Carbon Hub, 2010), advised the Government in 2011 that any future performance standards for zero carbon homes should be linked to *'as-built'* performance. In addition to this advice, the ZCH also set an ambition of being able to demonstrate that at least 90% of all new homes meet or perform better than the designed energy/carbon performance by 2020 (Zero Carbon Hub, 2014). Given the evidence currently available on the *'performance gap'*, with discrepancies in performance of more than 100% being reported (Zero Carbon Hub, 2010; Stafford, Bell & Gorse, 2012), this appears to be an ambitious target.

One factor that can contribute significantly to the *'performance gap'* is the thermal performance of the building fabric. In the UK, the thermal performance of dwelling fabric is extremely important, as dwellings not only tend to have long physical lifetimes, but the turnover (or demolition rate) of the domestic building stock is very low at around 20,000 dwellings per year (DCLG, 2008). Consequently by 2050, it is estimated that around 80-85% of the dwellings that will be lived in are already built and are standing today (Boardman, 2007; Killip, 2008).

Therefore, it is essential that ways are found to *'bridge'* the gap between the measured and the predicted fabric thermal performance of new build dwellings, otherwise we run the risk of creating a legacy of new dwellings that will have poorly performing building fabric for many decades to come.

Set within this context, the aim of this paper is to present the results from a series of building fabric tests that have been undertaken on a small number of case study dwellings in the UK, and compare these to a larger UK data set to establish whether it is possible to construct dwellings where the thermal performance of the building fabric as-built is comparable to that which has been predicted.

3 The test method

In order to assess the thermal performance of the building fabric, a series of fabric tests were undertaken on a small number of case study dwellings. All of the fabric tests formed a mandatory component of two separate Technology Strategy Board Building Performance Evaluation Programme studies. The aim of this programme was to understand the key factors that influence the in-use performance of buildings (Technology Strategy Board, 2010).

The first of the fabric tests to be undertaken was a coheating test. A coheating test is a quasi-steady state method that can be used to measure the aggregate *in situ* heat loss coefficient (HLC) of an unoccupied dwelling. It has existed in various forms since the late 1970's (see Sonderegger, Condon & Modera, 1979; Sonderegger & Modera, 1979; Ortega, Anderson, Connolly & Bingham, 1981), and remains one of the few methods that can be deployed in the field to measure whole dwelling heat loss. Although other methods are available, such as the PSTAR method (see Subbarao, 1988; Subbarao, Burch, Hancock, Lekov & Balcomb, 1988), or are currently under development, such as the QUB method (see Mangematin, Pandraud & Roux, 2012), their use has been limited in the UK.

A coheating test involves heating the inside of an unoccupied dwelling electrically, using thermostatically controlled point heaters, to an artificially elevated mean internal temperature. Air circulation fans are used to mix the internal air so that a uniform temperature distribution is achieved within the dwelling. The mean internal temperature is typically set at 25°C (at least a 10K temperature difference between the internal and external environment (ΔT) should be maintained throughout the test) and once the building fabric is in thermal equilibrium with the indoor conditions, the test is left to run for a specified period of time, typically set at around 1 to 3 weeks. In order to obtain a sufficient value of ΔT, the coheating test should be carried out in the winter months - in the UK this is usually between the months of October/November to March/April. During the test, a number of internal and external parameters are measured, these include: internal temperatures and relative humidity in all of the habitable rooms and circulation areas, the total electrical energy input to the dwelling, external temperature and relative humidity, external wind speed and direction, South-facing solar radiation and rainfall. The daily heat input to the dwelling (in W) that is required to maintain the artificially elevated mean internal temperature can then be determined from the measured daily total electrical energy input. If the daily heat input to the dwelling (in W) is plotted against the daily ΔT (in K), then the resulting slope of the plot gives the heat loss coefficient (HLC) for the dwelling in W/K.

Central to the analysis of the coheating test data is the assumption that the following energy balance holds true:

$$Q + R.S = (\Sigma U.A + C_v).\Delta T \tag{1}$$

Where:

Q = Total measured power input into the dwelling (W)

R = The solar aperture of the house (m^2)

S = The total amount of South facing solar radiation (W/m^2)

ΣU.A = Total fabric heat loss (W/K)

C_v = Background ventilation heat loss (W/K)

ΔT = Temperature difference between the inside and the outside of the dwelling (K)

There are, however, a number of limitations associated with undertaking a coheating test. The test requires the dwelling to be unoccupied throughout the test period. All lights and equipment within the dwelling need to be isolated during the test and entry to the dwelling restricted to the minimum required to ensure that the test is proceeding satisfactorily. Residual construction moisture within the dwelling also needs to have sufficiently dried-out prior to commencing the test otherwise the rate of heat loss measured could be exaggerated. Allowing the construction moisture to dry out also reduces the potential risk of surface condensation and mould growth occurring within the dwelling during the test. Tests normally need to be undertaken in winter months to minimise the impact of solar heat gains and to ensure that a sufficient daily average ΔT is maintained. The costs of undertaking a coheating test can often be prohibitive.

All of the coheating tests on the case study dwellings were undertaken in accordance with the 2010 version of Leeds Metropolitan University's coheating test method (Wingfield, Johnston, Miles-Shenton & Bell, 2010). During all of the coheating tests, the mean internal temperature setpoint was 25°C. This ensured that there was always at least a 10K ΔT between the inside and the outside of the case study dwellings throughout the test. All of the data obtained for the coheating test was analysed using multiple regression analysis with a forced zero intercept. In addition, the Siviour method of analysis (see Siviour, 1985) was also used to check the results obtained from the multiple regression analysis.

In parallel with the coheating test, two pressurisation tests were undertaken on the case studies dwellings; one undertaken immediately prior to, and the other immediately following the completion of the coheating test. Two separate tests were undertaken to establish whether the potential accelerated drying and associated shrinkage that may be caused by the mean elevated temperatures experienced during the coheating test had any impact on airtightness. The mean air leakage rate obtained from both tests was then averaged to obtain a mean air leakage rate over the coheating test period. All of the pressurisation tests were undertaken in accordance with ATTMA Technical Standard L1 (ATTMA, 2010) using an Energy Conservatory Model 3 Blower Door and a DG700 pressure/flow gauge. During the pressurisation tests, both a pressurisation and a depressurisation test were undertaken and the results averaged. This procedure is consistent with the advice given in CIBSE TM 23 (CIBSE, 2000).

A series of heat flux measurements were also undertaken during the coheating test period to determine the *in situ* U-value[i] of the main elements of the building fabric. The heat flux measurements were undertaken during the coheating test, as the conditions that are experienced during a coheating test (elevated and constant internal temperature) are conducive to obtaining accurate measurements of *in situ* U-values. The *in situ* heat flux and temperature measurements and U-value calculations were undertaken in accordance with ISO 9869:1994 (ISO, 1994). Heat flux was measured using Hukseflux HFP01 heat flux plates (HFPs). The HFPs were affixed to surfaces using adhesive tape and thermal contact paste. The voltage induced by the HFPs was recorded at one minute intervals by a Thermo Fisher Scientific dataTaker DT80 data logger. *In situ* U-values were corrected to account for the thermal resistance of the HFP (6.25 x $10^{-3}m^2K/W$). Positioning of the HFPs was informed by a thermographic survey, with HFPs being positioned in locations that were considered to be representative of the whole element, as well as other locations of particular interest, such as potential thermal bridges or anomalies. Portable air circulation fans were used during the coheating test to ensure even distribution of temperatures throughout the test dwellings and reduce stratification. Care was taken when positioning the HFPs to ensure that they were not unduly influenced by excessive air movement and direct radiant heat from heating elements. For instance, fans were positioned in such a way to ensure that air was not being blown directly on to the HFPs.

The high number of HFP locations meant that it was not practical to mount surface temperature thermocouples alongside each HFP; hence the air-to-air ΔT was measured in the vicinity of each HFP location. *In situ* U-values were calculated from measurements of heat flux density and ΔT using the average method contained within ISO 9869:1994. *In situ* U-values were measured over a minimum duration of fourteen 24 hour periods to minimise storage effects. The error associated with the *in situ* U-values presented was calculated to be 9%. This value was calculated as the quadrature sum of the uncertainties associated with the monitoring equipment and other sources of uncertainty listed in ISO 9869:1994.

The fabric tests were also supplemented by a significant amount of qualitative data. The qualitative data was collected both prior to and during the fabric tests to provide context and understand the as-built performance of the test dwellings. The data comprised:

- A photographic record of observations that were made during the construction phase.
- A series of infra-red thermographic surveys which were undertaken on different days and under various different environmental conditions to identify any thermal anomalies in the building fabric and identify any air leakage pathways during building depressurisation.
- Leakage detection, using a hand-held smoke puffer during building pressurisation, to identify the main air leakage points.

4 The case study dwellings

The fabric tests were undertaken on three separate new build case study dwellings, on two separate developments, all of which were designed to achieve Passivhaus Certification. Two of the dwellings (dwellings 1A and 1B) were located adjacent to one another on the same Passivhaus development. Details of the individual case study dwellings are contained within Table 1. As illustrated in Table 1, all three case study dwellings have a small floor area by UK standards.

Insert Table 1 here

Dwellings 1A and 1B were practically complete in early November 2011 and were tested over the period 8th November to the 22nd December 2011, inclusive. Dwelling 2 was practically complete in November 2012 and was tested over the period 8th to the 29th January 2013, inclusive. Further details regarding the case study dwellings and the duration of the individual tests can be obtained from Johnston & Fletcher (2013) and Johnston & Stevenson (2013).

5 Results and discussion of the building fabric tests

5.1 Pressurisation tests and leakage identification

The results obtained for the pre and post-coheating pressurisation tests are summarised in Table 2. The tests revealed that all of the test dwellings are very airtight by UK standards. Despite this, the figures obtained for Dwellings 1A and 1B are significantly higher than would normally be expected for Passivhaus dwellings. Part of the reason for this is likely to be attributable to the fact that these dwellings form part of a much larger terrace, where the primary air barrier has been designed to be continuous around the entire terrace, rather than around each individual dwelling contained within the terrace. Leakage detection, using hand-held smoke generators, revealed that the reason for the higher than expected air change rate was also probably attributable to small amounts of air leakage that were observed around a communal heat main that penetrated through the party wall in both dwellings. In addition, there was also some leakage through holes in the plasterboard dry-lining in the mezzanine loft space of both dwellings. These holes had been made to enable access to be gained to cables located within the service void. The results contained within Table 2 also revealed that in Dwellings 1A and 1B, there had been effectively no deterioration in airtightness as a result of the elevated temperatures experienced during the coheating test. This was not the case with Dwelling 2, where the air change rate of the dwelling increased slightly following completion of the coheating test. Thermal images revealed that this was likely to be attributable to additional air leakage making its way through the mitred joints on the fixed window lights, which had opened up as a result of the shrinkage/drying out that had occurred during the coheating test.

Insert Table 2 here.

A spot 50Pa pressure equalisation test was also undertaken on all of the case study dwellings to establish whether there was any inter-dwelling air leakage between the test dwelling and the adjacent dwellings. The equalisation test revealed small amounts of leakage between test Dwellings 1A and 1B and the adjacent dwellings. Further investigation using smoke detection revealed that this was likely to be caused by the inadequate sealing of the communal services located in the loft space as they pass through the party walls of each dwelling. No measurable air leakage was recorded between test Dwelling 2 and the adjacent mid-terrace dwelling.

5.2 Heat flux measurements

In total, 20 heat flux plates were positioned in both Dwelling 1A and Dwelling 2. As Dwelling 1B was of the same construction as Dwelling 1A, only 10 heat flux plates were installed in this dwelling. Details of the heat flux placement can be found within Johnston & Fletcher (2013) and Johnston & Stevenson (2013). It must be noted that the effective *in situ* U-values measured may not be fully representative of each thermal element for a number of reasons. These are as follows:

- It was only possible to undertake measurements of heat flux from a very small proportion of the total thermal element surface area in each test dwelling for a limited time period following building completion.
- The positioning of the HFPs was hampered, to varying degrees, by the form, orientation, internal layout and the location of internal fixtures and fittings within each of the test dwellings.
- The conditions (internal and external environmental, residual construction moisture) present during the heat flux measurement period may not be representative of the conditions under which the building is routinely subject to (commonly referred to as *'in service conditions'*).

A summary of the representative *in situ* U-values obtained from measurements of heat flux undertaken on the test dwellings are presented in Tables 3 and 4. The representative *in situ* U-values provided are either a single measurement obtained from a region of the thermal element that has been deemed to be representative of the entire element (i.e. not significantly affected by thermal bridging at junctions), or the mean of a number of measurement locations.

Insert Table 3 here.

Insert Table 4 here.

In Dwellings 1A and 1B, the heat flux density measurements revealed that in most cases the elements measured performed very closely to their specified design U-values, and no significant areas of unexpected heat loss were identified. The greatest variation between designed and calculated *in situ* U-value occurred at the ground floor and the first floor ceiling, both of which measured discrepancies in U-value of 0.02W/m^{2}K and 0.05W/m^{2}K respectively. The reasons for the large in relative terms but small absolute discrepancies in U-value are thought to be attributable to the fact that the heat flux plates on the ceiling and ground floor were located in close proximity to the eaves and the perimeter floor junction.

In Dwelling 2, the heat flux density measurements revealed that all the thermal elements measured, with the exception of the North-facing masonry cavity external wall, performed very closely to their specified design U-values. In terms of the masonry cavity external wall, a discrepancy equivalent to 0.06W/m^{2}K from the specified design U-value was measured in the location least influenced by thermal bridging. The reasons for the magnitude of this discrepancy could not be established using construction observations and non-destructive testing methods. However, thermal imaging from outside of the dwelling revealed the existence of a thermal anomaly on the external wall in the vicinity of where the internal heat flux measurements were taken. Unfortunately, placement of the heat flux plates in this location on the North-facing external wall was unavoidable, as it was severely restricted due to the form and orientation of the dwelling and the location of internal fittings within the test dwelling. As a consequence, it is likely that the measurements undertaken on the inside face of the North facing external wall are also likely to have been influenced to some degree by thermal bridging at the large number of junctions and openings on this wall.

5.3 Thermographic surveys

The infra-red thermographic surveys were undertaken using a Flir B620 thermal imaging camera in accordance with the guidance set out in BSRIA Guide 39/2011 (Pearson, 2011). Overall, the thermographic surveys revealed few thermal anomalies. This is as expected given the results of the coheating tests. In Dwellings 1A and 1B, no significant areas of unexpected heat loss were identified. The only areas where a small amount of unexpected heat loss was observed was in Dwelling 1A at the jambs of the West-facing window (both internally and externally), in Dwelling 1A at the jamb of the window in the rear bedroom (internally only), and at the external door handles and door thresholds in both dwellings.

Thermal imaging did reveal a number of areas of unexpected heat loss in Dwelling 2. The most significant area was at the external wall/eaves junction (both internally and externally) where the insulation had not been extended fully into the eaves. A temporary loft hatch had also been made in the test dwelling and remedial works had been undertaken to attempt to rectify the insulation. Despite the remedial work, subsequent thermographic surveys still identified some unexpected heat loss at this junction, although to a much lesser degree than was previously the case. Other areas of unexpected heat loss included: two spots above the utility area at intermediate floor height, a spot on the North facing external wall in the vicinity of the internal heat flux measurements, at lintel edges (particularly on the gable wall), at the MVHR system exhaust and supply grilles (externally) at the soil pipe roof penetration, at the eaves junction to the North façade, at the external door handles (internally) and around the temporary loft hatch (internally).

5.4 Coheating tests

To minimise inter-dwelling heat transfer via party elements during a coheating test, it is common practice to heat any adjacent dwellings to the same mean internal temperature as the test dwelling. Unfortunately, the adjoining dwellings to Dwelling 1B and Dwelling 2 were both occupied during the test period, so it was not possible to maintain isothermal conditions between the test dwellings and the adjacent occupied dwellings. Despite this limitation, it was possible to install an array of HFPs on the party wall of Dwelling 2 to measure the amount of heat flux through this wall. In addition, a number of temperature sensors were also installed in the adjacent dwelling in those areas that shared the party wall with the test dwelling. Analysis of the temperature data revealed that the adjacent dwelling was consistently maintained at a lower temperature than the test dwelling, so the direction of heat flow was always from the test dwelling to the adjacent dwelling. The average flux density measured through the party wall HFPs was then used in conjunction with the ΔT between the dwellings to determine the average amount of additional power that was being lost through the party wall of the test dwelling to the adjacent dwelling. This additional power was then subtracted from the measured power input into Dwelling 2 in the analysis of the coheating data as this element did not act as external heat loss element.

In Dwellings 1A and 1B, an array of HFPs was installed on both sides of the party wall between both dwellings. These two arrays were installed to determine whether there was any unaccounted heat transfer through the party wall due to thermal bridging and/or thermal bypassing. For the majority of the coheating test period, very small amounts of positive flux (~0.3W/m^2) were measured from all of the HFPs located on the party wall, in both dwellings, indicating that there was no inter-dwelling heat transfer between the dwellings and that the party wall was in fact acting as a heat loss mechanism. Unfortunately, it was not possible to install any HFPs on the party wall between Dwelling 1B and the adjacent dwelling. Despite this, a number of temperature sensors were installed in the dwelling adjacent to Dwelling 1B, which revealed that the mean elevated temperature in the adjacent dwelling was on average 0.7°C warmer than that in Dwelling 1B. Taking into consideration the area and design U-value of the party wall (29.3m^2 and 0.22W/m^{2}K), the maximum amount of flux that could have been transferred from one dwelling to the other would have been less than 5W. It is quite possible that less than 5W would have transferred through this party wall, as the construction was identical to that between Dwelling 1A and 1B, so it is highly likely that it would also have acted as a heat loss mechanism. Consequently, no corrections have been made to the measured power input into Dwellings 1A and 1B in the analysis of the coheating data.

The results of the coheating tests for all three test dwellings are detailed within Table 5, along with the standard error obtained from the regression analysis in Figures 1 to 3. For comparative purposes, Figures 1 to 3 and Table 5 also show the predicted steady state heat loss coefficient (HLC) for all three test dwellings. The predicted steady state HLC is an informed estimate based upon what was actually built and observed on-site. It comprises both a fabric and a background ventilation HLC. The fabric HLC has been determined from the plane element U-values, the areas of each element (walls, floor, roof, doors and windows) and the heat losses attributable to thermal bridging. In most instances, the plane element U-values have been obtained from the design data for each development. The only exception to this is where differences in the construction detailing or the materials used have been identified from the site observations. In such cases, the U-values have been recalculated in accordance with BS EN ISO 6946:2007 (BSI, 2007), based upon what was observed on-site. With respect to thermal bridging, all of the individual thermal bridges for each junction within each dwelling have been modelled explicitly using Physibel TRISCO version 12.0w software (Physibel, 2010) in accordance with the conventions given in BR 497 (Ward & Sanders, 2007), where appropriate. This has enabled the Ψ-value[ii] attributable to each junction to be determined. A measured survey of all three test dwellings was also undertaken to determine the actual area of each of the building elements and the length of the junctions as-built, rather than relying upon the data contained within the design or as-built drawings.

The background ventilation HLC has been calculated based upon the mean air leakage rate of the test dwellings in h^{-1} @ 50Pa over the coheating test period. The mean air leakage rate has been approximated to a background ventilation rate using the simple n50/20 *'rule of thumb'* (see Sherman, 2008), which states that the natural annual average background ventilation rate can be approximated by simply dividing the air change rate at 50Pa (n50) by 20. In addition, some assumptions regarding the number of sides of the dwelling that are sheltered have also been made. In Dwelling 1A and Dwelling 2 (end-terraced dwellings), it has been assumed that two sides of the dwelling are sheltered, whilst in Dwelling 1B (mid-terraced dwelling), it has been assumed that three sides of the dwellings are sheltered.

Insert Table 5 here.

The results contained within Table 5 reveal a difference between the measured and the predicted HLC in all cases, with the measured HLC being greater than that predicted. This was expected, as it is not possible for the measured HLC to be lower than the predicted HLC. If this is the case, then the model or data used to predict the HLC is incorrect. On first glance, the discrepancy observed in Table 5 between the measured and the predicted performance of test Dwelling 1A and Dwelling 2 does appear to be rather large, at 16% and 18%, respectively. However, this is more a consequence of the fact that both test dwellings have such a very low predicted heat loss coefficient to begin with (40.3W/K and 40.0W/K, respectively), so any observed difference between the measured and the predicted performance will appear to be disproportionately large. Closer examination of the results reveals that the absolute difference in HLC measured for all of the test dwellings is in fact very small, ranging from 2.3W/K for Dwelling 1B to 7.3W/K for Dwelling 2. However, a degree of caution should be exercised when utilising a metric such as HLC, as it does not take into consideration dwelling size or form, so tends to penalise larger dwellings and those that have a large surface to volume ratio. In this case, HLC has only been used to compare measured against predicted performance, and no attempt has been made to identify the most efficient building envelope. An alternative metric, which could be used, would be average U-value.

5.5 Coheating results in context

To put the coheating results obtained for the test dwellings in context, the measured and predicted whole house HLC for the test dwellings is illustrated in Figures 4, 5 and 6, alongside the coheating test results of 22 other new build dwellings, all of which were built to meet Part L1A of the UK Building Regulations 2006 (NBS, 2006) or better, and all of which were tested previously by the same organisation shortly after practical completion. The new build coheating test results have been obtained from one of the largest and most comprehensive databases of coheating test information on dwellings in the UK. The database has been populated over a period of approximately ten years, and contains information on 25 new build dwellings of different age, size, type and construction, as well as data on a wide range of existing dwellings. Despite this, the sample size of the database is small, highlighting the practical difficulties associated with obtaining such data on dwellings in the UK. It should also be noted that the dwellings contained within the database are not the result of random sampling, so the results cannot be qualified as being representative of the UK housing stock as a whole.

In fact, as a significant proportion of the dwellings contained within the database were built to exceed the requirements of the UK Building Regulations that were in force when they were constructed (Part L1A 2006 or better), the database is likely to be biased towards dwellings that were designed to have much higher levels of fabric performance than those which would normally have been required for compliance purposes alone. This should be taken into consideration when interpreting the results discussed below.

An analysis of the data contained within Figure 4 indicates that a very wide range of performance exists within the database of coheating test results, with the measured performance exceeding the predicted performance in all of the dwellings. In the majority of cases, the difference between the predicted and measured performance is considerable; on average the measured fabric performance within the database was 50% greater than that predicted. Despite this, it is clear that the case study dwellings are the best performing dwellings in the sample, both in terms of predicted and measured performance, by some considerable margin. This is not surprising given that the case study dwellings have a small floor area and are all Passivhaus Certified, so were designed at the outset to have a very low predicted HLC. The results obtained from the various building fabric tests (pressurisation tests and leakage identification, heat flux measurements and thermal imaging surveys) also indicated that the case study dwellings performed very well *in situ*.

Closer analysis of the coheating data illustrates the size of the *'gap'* in percentage terms that exists between the measured and predicted steady state performance (see Figure 5). This analysis reveals that the size of the *'gap'* varies considerably, ranging from just over 6% to just under 140%, with a median of 34.5%. In comparison to all of the other new build dwellings contained within the database, the size of the *'gap'* observed for all of the case study dwellings is relatively small, particularly when one considers that for these dwellings, the gap tends to be disproportionately large in percentage terms due to their very low predicted HLC. If the data is also analysed in terms of the absolute difference in HLC in W/K, the absolute difference measured for all three case studies is almost negligible (see Figure 6), particularly in comparison to the majority of the other dwellings contained within the coheating test database.

6. Conclusions

The results from the coheating tests revealed that all of the case study dwellings tested performed very close to that predicted. This was despite the fact that significant relative differences in U-value performance were measured for some of the fabric elements, for instance the ceiling and ground floor of Dwellings 1A and 1B. Although the relative differences in U-value performance were large, the differences were very small in absolute terms and were most probably attributable to restrictions imposed on the placement of the heat flux sensors. It is also important to note that the results obtained for the case study dwellings are also in contrast with the remaining data on new build dwellings that is contained within the coheating database; the largest database of its kind in the UK. If one also considers that the coheating database is likely to be biased towards more highly insulated and airtight dwellings than is the norm for compliance purposes, then the fabric performance results achieved in the case study dwellings become even more significant.

Although it is recognised that the results presented come from a very small non-random sample, the authors believe that these results are extremely important, both in the context of the UK and internationally, as they are one of the first to indicate that it is practically possible to *'bridge the gap'* between the measured and the predicted fabric thermal performance of new dwellings.

Although it is difficult to establish the precise reasons why the case study dwellings perform as well as they do, it is thought that it is most likely attributable to a combination of three main factors. First of all, as the intention was to gain Passivhaus Certification for all of the case study dwellings, various additional quality control processes were required to be implemented during the design and construction process in order to achieve certification. For instance, a photographic and documentary record of the construction process was required to be kept and any changes made to the building fabric during the construction phase were evaluated to ascertain whether they would have a detrimental impact on the thermal performance of the building envelope. These processes would not normally be implemented in the mainstream construction of housing, either in the UK or abroad. Secondly, all of the case study dwellings were designed and built by a highly skilled, educated and committed set of individuals. Consequently, considerable care and attention went into the design and construction of the dwellings to ensure that any potential issues, such as thermal bridging, were minimised and that Passivhaus Certification could be attained. Thirdly, as both developments were high profile projects that were subject to media attention, if the case study dwellings failed to perform as anticipated then the 'cost of failure' would have been much greater than would normally be the case in conventional mainstream housing and is much more likely to have been noticed by the occupants of the dwellings.

Another important key finding from this study is the importance of testing the thermal performance of the building fabric of new buildings *in-situ*. In the absence of some form of compulsory testing, it is difficult to know whether the fabric of the constructed building is likely to perform as predicted, and if it is not, the specific reasons why not. Other techniques are available that are capable of assessing whether a building is likely to perform *in-situ*, such as energy signature analysis, however it is not possible to establish the reasons for any potential discrepancies in fabric thermal performance using such techniques. If *in situ* performance testing is to become compulsory, then agreed test procedures and standards will need to be developed for those tests where such procedures and standards do not currently exist, for example, the coheating test. A draft CEN (European Committee for Standardisation) standard on the *'In situ measurement of thermal performance –Testing of completed buildings'* is currently under development. In addition to this, a number of the limitations associated with the coheating test will also need to be addressed.

Finally, although the case study dwellings illustrate that it is practically possible to construct dwellings where the building fabric performs as well as predicted, the key challenge for the industry, both in the UK and abroad, will be to replicate this success in the mainstream construction of housing. If this is to be achieved, a cultural shift will be required within the industry, towards more performance based construction, where testing of the as-built energy and thermal performance of the building becomes more prevalent, and the results from such tests are fed back into the design and construction process. It is also likely to require a more highly skilled and educated workforce than is currently the case, coupled with the widespread adoption of new practices and procedures, particularly in relation to quality control, such as those currently required to achieve Passivhaus Certification. If such changes can be made by the industry in the UK, and the gaps in performance relating to the energy use of the buildings services are also addressed, then it could be possible to meet the Zero Carbon Hub's (Zero Carbon Hub, 2014) ambition of demonstrating that at least 90% of all new homes meet or perform better than the designed energy/carbon performance by 2020 (Zero Carbon Hub, 2014).

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Endnotes

i U-value is the rate of heat flow in watts (W), through $1m^2$ of an element, when there is a temperature difference across the element of 1 K. Measured in W/m^2K.

ii Ψ-value (psi value) is the rate of heat flow per degree temperature difference per unit length of a thermal bridge. Measured in W/mK.

Table 1: Details of the case study dwellings.

	Dwelling 1A	**Dwelling 1B**	**Dwelling 2**
Form	End-terraced bungalow	Mid-terraced bungalow	End-terrace
No. of storeys	1 plus mezzanine plant area	1 plus mezzanine plant area	2
Total floor area (m^2)	66	66	65
Envelope area (m^2)	246	245	177
Volume (m^3)	248	246	157
Main construction type	Pre-fabricated timber-frame cassette, reinforced concrete ground bearing floor slab, timber-frame cassette pitched roof insulated at the roof slope.	Pre-fabricated timber-frame cassette, reinforced concrete ground bearing floor slab, timber-frame cassette pitched roof insulated at the roof slope.	Full fill masonry cavity external walls, reinforced concrete ground bearing floor slab, bobtail trussed rafter pitched roof construction insulated at the ceiling level.
No. of bedrooms	2	2	2
Orientation (living area)	South/North	South/North	South/North

Table 2: Pressurisation test results.

Dwelling	Depressurisation only (h^{-1} @ 50Pa)	Pressurisation only (h^{-1} @ 50Pa)	Mean Air Leakage Rate (h^{-1} @ 50Pa)	Comment
Dwelling 1A	0.83	0.93	0.88	Pre-coheating test
	0.90	0.86	0.88	Post-coheating test
Dwelling 1B	1.32	1.29	1.30	Pre-coheating test
	1.32	1.29	1.30	Post-coheating test
Dwelling 2	0.60	0.62	0.61	Pre-coheating test
	0.62	0.71	0.66	Post-coheating test

Table 3: Summary of design and *in situ* effective U-values obtained from heat flux measurements for Dwellings 1A and B.

Thermal element	**Design U-value (W/m^2K)**	**Representative *in situ* U-value (W/m^2K)**	**Notes**
External wall (North-facing)	0.10	0.10	Mean of 4 no. U-value measurements. Max U-value 0.10 W/m^2K Min. U-value 0.10 W/m^2K. Sample SD 0 W/m^2K.
Ground floor	0.08	0.10	Mean of 2 no. U-value measurements. Max U-value 0.11 W/m^2K Min. U-value 0.09 W/m^2K.
Roof (first floor ceiling)	0.08	0.13	Mean of 3 no. U-value measurements. Max U-value 0.15 W/m^2K Min. U-value 0.10 W/m^2K. Sample SD 0.03 W/m^2K.

Table 4: Summary of design and *in-situ* effective U-values obtained from heat flux measurements for Dwelling 2.

Thermal element	**Design U-value (W/m^2K)**	**Representative *in situ* U-value (W/m^2K)**	**Notes**
External wall (North-facing)	0.12	0.18	Representative U-value is based on one measurement location. 24 hour U-value SD 0.01 W/m^2K.
Ground floor	0.12	0.14	Mean of 2 no. U-value measurements. Max U-value 0.15 W/m^2K Min. U-value 0.13 W/m^2K.
Roof (first floor ceiling)	0.09	0.09	Mean of 2 no. U-value measurements. Max U-value 0.10 W/m^2K Min. U-value 0.08 W/m^2K.

Table 5: Results of the coheating tests.

Dwelling	Measured Heat Loss Coefficient (W/K) – from coheating test	Predicted Heat Loss Coefficient (W/K) – from design data and site observations	Difference in Heat Loss Coefficient (%)	Absolute difference in Heat Loss Coefficient (W/K)
1A	46.6 ±0.5	40.3	15.6	6.3
1B	38.1 ±0.5	35.8	6.2	2.3
2	47.3 ±0.5	40.0	18.3	7.3

Figure 1: Corrected heat loss data for Dwelling 1A.

Figure 2: Corrected heat loss data for Dwelling 1B.

Figure 3: Corrected heat loss data for Dwelling 2.

Figure 4: Measured versus predicted HLC of the new build coheating database.

Figure 5: Comparative difference in the measured versus predicted HLC of the dwellings contained within the new build coheating database.

Figure 6: Absolute difference between the measured and predicted HLC of the dwellings contained within the new build coheating database.