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Post construction thermal testing: Some recent measurements

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Abstract

In the UK, it has become apparent in recent years that there is often a discrepancy between the steady state predicted and the measured *in situ* thermal performance of the building fabric, with the measured *in situ* performance being greater than that which has been predicted. This discrepancy or '*gap*' in the thermal performance of the building fabric is commonly referred to as the building fabric '*performance gap*'. This paper presents the results and key messages that have been obtained from undertaking a whole building heat loss test, a coheating test, on seven new build dwellings as part of the Technology Strategy Board's Building Performance Evaluation Programme. While the total number of dwellings involved in the work reported here is small, the results illustrate that a wide range of discrepancies in thermal performance was measured for the tested dwellings. Despite this, the results also indicate that it is possible to construct dwellings where the building fabric performs thermally more or less as predicted, thus effectively bridging the traditional building fabric '*performance gap*' that exists in mainstream housing in the UK.

Keywords chosen from ICE Publishing list

Energy; field testing & monitoring; thermal effects.

List of notation

ΔT is the difference between the mean internal and external air temperature.

1. Introduction

In response to concerns regarding stabilisation of atmospheric greenhouse gas concentrations and the potential risks posed by climate change, the UK Government published the Climate Change Act in 2008 (HMSO, 2008). This was the world's first legally-binding national framework designed to reduce anthropogenic greenhouse gas emissions. The Act committed the UK Government to at least an 80% reduction in national Carbon Dioxide (CO₂) emissions by 2050 based on 1990 levels. It also introduced a series of five year carbon budgets covering the period up to and including the year 2050, along with an interim target of at least a 34% reduction in national CO₂ emissions by 2020, based on 1990 levels. Achieving such significant reductions in CO₂ emissions in practice is likely to be technically demanding and will require reductions across all sectors of the economy.

In the UK, one sector which contributes significantly to national energy use and CO₂ emissions is the domestic sector. Currently, there are over 27 million dwellings in the UK (Palmer & Cooper, 2013) which account for just under 30% of the UK's total energy consumption (DECC, 2014) and total CO₂ emissions (DECC, 2013). Within the domestic sector, the largest single end-use category is space heating, accounting for approximately 62% of all of the energy delivered to the existing housing stock in 2011 (Palmer & Cooper, 2013). Clearly, if we are to mitigate the effects of climate change and achieve the UK Government's 80% national CO₂ emission reduction target, then significant reductions in the energy use and carbon emissions related to domestic space heating are likely to be required.

One factor that can have a very important influence on the energy use and carbon emissions attributable to domestic space heating is the thermal performance of the building fabric. In the UK, the thermal performance of the building fabric is very rarely measured *in situ*, so is often assumed to perform thermally as the design originally intended. However, there is a growing body of evidence that suggests that this is often not the case, (see Hens *et al.*, 2001 & 2007 and, Doran & Carr, 2008) not least because the original design intent can often change during construction. Measurements undertaken in the field have revealed that a discrepancy often exists between the steady state predicted thermal performance of the building fabric as built and the measured *in situ* thermal performance of the building fabric, with the measured *in situ* thermal performance as built being greater than that which has been predicted (see Stafford *et al.*, 2012 and Zero Carbon Hub, 2010). This discrepancy or '*gap*' in the thermal performance of the building fabric is commonly referred to as the building fabric thermal '*performance gap*'. This is just one of a number of '*performance gaps*' that can exist in buildings. Others relate to the energy performance of the building services and energy supply systems and occupancy.

The existence of the building fabric thermal '*performance gap*' is not a new phenomenon, although it is rarely understood. At the scale of individual building elements, *in situ* U-value

measurements undertaken on various different external walls by Bankvall (1978), Lecompte (1990), Doran (2001), Hens *et al.* (2001 & 2007), Doran & Carr (2008) found that the U-values measured in the field were often higher than those expected when compared to their calculated equivalents. At the whole building scale, recent field measurements undertaken on whole dwelling heat loss have illustrated that there can be a large gap between the measured and the predicted thermal performance of the whole building envelope, and in some cases, this difference can be greater than 100% (see Stafford *et al.*, 2012 and Zero Carbon Hub, 2010). Clearly, differences in the thermal performance of whole buildings of this order of magnitude will have a significant impact on the dwellings associated energy use and CO₂ emissions, and it is highly probable that they could also have a detrimental impact on occupant thermal comfort.

It is also important to realise that dwellings in the UK tend to have long physical lifetimes, particularly in comparison to other building types, and domestic demolition rates are currently very low at approximately 20,000 dwellings per year (DCLG, 2008). Consequently, it is estimated that somewhere between 80-85% of all of the dwellings that are currently built and standing today, will still be standing and lived in by the middle of this century (Boardman, 2007 & Killip, 2008). Therefore, if we do not begin to address the issues associated with the building fabric thermal '*performance gap*', then there is a risk that we will end up constructing dwellings with poor levels of building fabric thermal performance that will be standing and lived in for generations to come.

Set within this context, this paper presents the results and key messages that have been obtained from undertaking a whole building heat loss test, known as a coheating test, on a small number of case study dwellings in the UK, and compares the results to a larger UK data set.

2. The test method

A range of techniques are available that are capable of measuring various different aspects of the energy and thermal performance of the building fabric once constructed. The majority of the techniques available are only capable of measuring a particular aspect of the thermal performance of a whole building, such as the rate of heat flux through an external wall, so tend to disaggregate heat loss in to its constituent components. These techniques include pressurisation testing, leakage detection, heat flux measurement, thermal imaging, tracer gas measurement, cavity temperature measurement, air flow measurement and partial deconstruction of the building envelope. In addition to these disaggregate techniques, a limited number of aggregate techniques also exist that are capable of measuring the heat loss attributable to an entire building. These include the Primary and Secondary Terms-Analysis and Renormalization (PSTAR) method (Subbaro, 1988 & Subbaro *et al.*, 1988), ISABELE (Bouchié *et al.*, 2014), the Quick U-value of Buildings (QUB) method (Mangematin *et al.*, 2012) and the coheating test method (Wingfield *et al.*, 2010 and Johnston *et al.*, 2013). Of these methods, the PSTAR method has seen limited application in the UK, whilst the QUB and ISABELE method

are both currently under development. The only method that has seen considerable development and application in the field in the UK is the coheating test method. Coheating tests also formed a key component of the Post Construction and Early Occupation studies that were undertaken as part of the Technology Strategy Board's recent Building Performance Evaluation Programme (Technology Strategy Board, 2010). Given this, in order to be able to measure the aggregate thermal performance of the building fabric, a coheating test has been undertaken on each of the case study dwellings.

A coheating test is a quasi-steady state test method that can be applied in the field to an unoccupied building to measure the aggregate whole dwelling heat loss (both fabric and background ventilation). The method is classed as a quasi-steady state test method, as the internal environment is controlled such that it is in a steady state condition, whilst the external environment varies dynamically in response to the external climatic conditions. The coheating test was originally developed in the late 1970's in North America (see Socolow, 1978; Sonderegger & Modera, 1979 and Sonderegger *et al.*, 1980) to investigate the efficiency of space heating systems, and involved the simultaneous heating of a building using the installed heating system and portable electric resistance heaters, hence the use of the name "*coheating*". In the UK, the earliest documented use of the test method was in the 1980's (see Siviour, 1985 and Everett, 1985), where the method was developed to measure the aggregate heat loss from a dwelling using portable electric resistance heaters only. Following very limited use of the test method in the 1990's (for example: Bell & Lowe, 1997), it has only been in the last decade or so that the method has been applied in the field in any significant number of instances, culminating in the development of a recognised experimental test method (see Wingfield *et al.*, 2010).

The current version of the coheating test method described by Johnston *et al.* (2013) involves using portable electric resistance point heaters to heat the inside of an unoccupied dwelling to a specified artificially elevated mean internal temperature, typically for a period of between 1 to 3 weeks. In the UK, a mean internal setpoint temperature of 25°C is commonly used, as it is within the expected range of temperatures that would normally occur within the building during occupation¹, and ensures that there is a sufficient temperature difference between the inside and outside of the building (ΔT) such that heat flow is primarily driven out through the building fabric. In the UK, tests are normally only undertaken during the heating season (October/November to March/April), in order to ensure that a sufficient value of ΔT ($\geq 10K$) is maintained throughout the test. By measuring the total amount of electrical energy that is required to maintain the artificially elevated mean internal temperature each day, the daily heat input to the building (in Watts) can be established. The heat loss coefficient (W/K) for the building can then be determined by plotting the daily heat input in Watts against the daily difference in temperature (ΔT) in Kelvin. The resulting gradient of the plot gives the raw

¹ A higher setpoint temperature that is outside the range of temperatures normally experienced during occupation, may result in accelerated shrinkage and drying out of the building fabric.

uncorrected heat loss coefficient in W/K and provides an estimate of the steady state rate of heat loss from the whole dwelling per Kelvin. The uncorrected raw data can then be corrected using multiple linear regression analysis techniques to take account of external environmental effects such as solar radiation. An example of a plot using the multiple linear regression analysis method to account for solar radiation is illustrated in Figure 1.

3. Case study dwellings

The coheating tests were undertaken on seven case study dwellings, located on five separate developments in the North of England. All of the dwellings were tested as part of the Technology Strategy Board's Building Performance Evaluation Programme and as a minimum were designed to exceed the insulation standards contained within the 2006 Edition of the Building Regulations Approved Document Part L1A (NBS, 2006). Details of the individual case study dwellings are contained within Table 1 and Table 2.

As illustrated in Table 1, it is clear that a range of design standards were adopted for the case study dwellings. Three of the dwellings (1A, 1B & 2) were designed to achieve Passivhaus Certification. Of the remaining four dwellings, two of the dwellings were designed to the Code for Sustainable Homes Level 4 (4 & 5) and two of the dwellings were designed to the Code for Sustainable Homes Level 5 (3A & 3B). The Code For Sustainable Homes (CSH) is an environmentally based rating system for new homes that awards points (up to a maximum of 100) based upon nine categories: energy and CO₂ emissions, water, materials, surface water run-off, waste, pollution, health and well-being, management and ecology. To obtain CSH Level 4, 68 points are required, whilst Level 5 requires 84 points. Category 1 for energy and carbon dioxide emissions is heavily weighted and uses the Dwelling CO₂ Emissions Rate (DER) and the Fabric Energy Efficiency (FEE) calculated in SAP to assign CSH points. Therefore, any potential changes to the DER and FEE that are related to a building's fabric thermal performance will affect the overall CSH rating. The research for this paper has not assessed the impact on the CSH rating awarded but highlights that the levels of building fabric thermal performance achieved can vary from the design intent. It is also important to note that the three Passivhaus case study dwellings (1A, 1B & 2) also have a small floor area by UK standards.

Table 1: Details of the case study dwellings.

Dwelling	Form	No. of storeys	Main external wall construction	Gross floor area (m ²)	Design standard	Test period
1A	End-terraced bungalow	1 plus mezzanine plant area	Pre-fabricated timber-frame cassette	66	Passivhaus	8/11/11 – 22/12/11
1B	Mid-terraced bungalow	1 plus mezzanine plant area	Pre-fabricated timber-frame cassette	66	Passivhaus	8/11/11 – 22/12/11
2	End-terrace	2	Full fill masonry	65	Passivhaus	8-29/1/13

			cavity			
3A	Semi-detached	2	Full fill masonry cavity	93	Code for Sustainable Homes Level 5	23/10/12-19/12/12
3B	Semi-detached	2	Full fill masonry cavity	93	Code for Sustainable Homes Level 5	23/10/12-19/12/12
4	Semi-detached	2	Partial fill thin joint masonry cavity	90	Code for Sustainable Homes Level 4	08/03/13-04/03/13
5	Detached bungalow	1	Hemcrete	157	Code for Sustainable Homes Level 4	01-25/02/11

Table 2: Main construction types and design U-values for the case study dwellings.

Dwelling	Ground floor	External walls	Roof
1A & 1B	Reinforced concrete ground bearing floor slab, with 300mm insulation above the slab and 50mm screed. U-value of 0.08 W/m ² K.	Pre-fabricated timber-frame cassettes filled with 300mm insulation and clad externally with 15mm bitroc and brick or render. Internally, a 47mm insulated service void lined with 25mm plasterboard. U-value of 0.10 W/m ² K.	Pre-fabricated timber-frame cassette filled with 450mm insulation and clad in clay roof tiles. U-value of 0.08 W/m ² K.
2	22 mm thick tongue and grooved softwood floating floor over 150 mm reinforced concrete ground bearing floor slab on 250 mm of EPS insulation. U-value of 0.12 W/m ² K.	Two coat wet plaster internal wall finish, 100 mm blockwork, 300 mm cavity fully-filled with mineral wool insulation, 100 mm blockwork and an 8-10 mm render, U-value of 0.12 W/m ² K.	Bobtail trussed rafter pitched roof construction insulated at ceiling level with 500 mm of mineral wool insulation quilt. U-value of 0.09 W/m ² K.
3A & 3B	Pre-cast concrete beam and block floor with insulation below a 75 mm concrete screed. U-value of 0.20 W/m ² K.	Plasterboard on dabs with finish plaster, 100 mm autoclaved aerated concrete (AAC) blockwork, 100 mm cavity fully-filled with mineral wool insulation and a brickwork outer leaf. U-value of 0.26 W/m ² K.	A timber trussed rafter cold pitched roof structure clad with concrete roof tiles. The roof is insulated at ceiling level with 400 mm of mineral wool. U-value of 0.11 W/m ² K.
4	Pre-cast concrete beam with expanded polystyrene composite flooring system and 75 mm reinforced structural screed. U-value of 0.16 W/m ² K.	Plasterboard on dabs with finish plaster, 3 mm parge coat, 100 mm autoclaved aerated concrete thin joint blockwork, 100 mm polyisocyanurate insulation, 50 mm cavity and a brickwork outer leaf. U-value of 0.17 W/m ² K.	A timber trussed rafter cold pitched roof structure clad in clay roof tiles. The roof is insulated at ceiling level with 300mm mineral wool. U-value of 0.14 W/m ² K.
5	Pre-cast concrete beam and block floor with insulation below a screed with under floor heating	9mm magnesium silicate board finished with a lime-based plaster, 89 x 38mm timber frame filled	A timber trussed rafter cold pitched roof structure clad in clay concrete tiles. The roof is

	pipes, U-value of 0.12 W/m ² K.	with 300mm of Tradical® Hemcrete® at a density of 275kg/m ³ and clad externally in softwood or a lime-based render. U-value of 0.19 W/m ² K.	insulated at ceiling level with 300mm mineral wool. U-value of 0.10 W/m ² K.
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4.1 Results of the coheating tests

The coheating test results for all seven case study dwellings are illustrated in Figure 2. For comparative purposes, the measured heat loss coefficient (HLC) obtained from the coheating test has been compared against the design intent HLC and the predicted steady state HLC. The design intent HLC has been obtained from the design based SAP assessments that were submitted for compliance purposes and represent the original design intent for each of the case study dwellings. The predicted HLC was calculated using a basic steady state model; the same as that used by SAP for quantifying the building fabric HLC. This approach was taken for two main reasons. First of all, so that a direct comparison could be made between the design intent HLC found in the design based SAP assessments for the case study dwellings and the predicted HLC). Secondly, the coheating test replicates the homogenous internal environment assumed by a SAP based U-value x Area calculation. The model for calculating the predicted HLC focuses on conductive losses with allowances made for some radiative and convective losses in the parameters input into the plane element U-value calculations. Heat loss by advection is accounted for in the air change rate caused by infiltration (air permeability). The UK construction industry is familiar with the steady state model that forms the basis of all energy use and CO₂ assessments undertaken for dwellings within the UK.

The predicted steady state HLC is a well-informed estimate of the fabric and background ventilation HLC attributable to the case study dwellings that is based upon what was physically observed as built on-site. Consequently, in the majority of cases, the predicted steady state HLC differs from the original design intent HLC. The predicted fabric HLC is an estimate that has been calculated from measured survey data, the U-values of the plane elements and thermal bridging calculations that have been informed by the on-site observations. The plane element U-values were calculated using version 2.03 of the Building Research Establishment (BRE) U-value calculator (BRE, 2011) in accordance with BS EN ISO 6946:2007 (BSI, 2007) and BR 443 (Anderson, 2006). The thermal bridging calculations were prepared by thermally modelling the junctions using the Physibel TRISCO version 12.0w software (Physibel, 2010) in accordance with the conventions set out by BR 497 (Ward & Sanders, 2007). The predicted background ventilation HLC has been approximated for each of the case study dwellings by taking the measured mean air leakage rate in h⁻¹ @ 50Pa (n₅₀), which has been obtained by undertaking a pressurisation test² in accordance with ATTMA Technical Standard L1 (ATTMA,

² This involves measuring and recording the airflow rate that is required to maintain a number of positive and negative pressure differences across the building envelope using a portable variable speed fan, which is sealed into an external

2010), and dividing by 20 using the simple $n_{50}/20$ 'rule of thumb' (see Sherman, 1998). In addition, assumptions had to be made on the number of sheltered sides that applied to each dwelling. The approach taken to determine the number of sheltered sides was in accordance with the conventions set out in the Government's Standard Assessment Procedure (BRE, 2009).

The results contained within Figure 2 illustrate that not only did the case study dwellings vary considerably in terms of their overall designed, predicted and measured performance, but most importantly, the measured performance exceeded the predicted performance in all cases. This suggests that a building fabric 'performance gap' exists in all of the case study dwellings. Closer analysis of the data reveals that the size of the gap in percentage terms varies significantly, from just over 6% for Dwelling 1B to just over 63% for Dwelling 5. However, caution needs to be applied when utilising such a metric, as it tends to unfairly penalise larger dwellings, those that have a large surface to volume ratio and those dwellings that have a very low predicted steady state HLC to begin with, such as Dwellings 1A, 1B and 2. A more appropriate metric may be to use the absolute difference in HLC between the measured and predicted performance. If such a metric is used, then the difference in overall HLC that was measured for Dwellings 1A, 1B and 2 is very small at 6.3, 2.2 and 7.3W/K respectively, particularly when compared to the difference in HLC measured for Dwelling 5 of almost 86W/K. If one also takes into account the various uncertainties associated with coheating testing, then the size of the building fabric 'performance gap' measured for case study Dwellings 1A, 1B and 2 can be considered to be negligible, indicating that the building fabric associated with these dwellings is performing *in situ* pretty much as predicted. The reasons why Dwellings 1A, 1B and 2 have such a very low predicted steady state and measured HLC are due to the fact that these case study dwellings are all Passivhaus Certified, so were designed to have very low plane element U-values and very high levels of airtightness in the first place. In addition, during the construction of the dwellings, various quality control processes that would not normally be implemented in mainstream housing were required to be implemented, in order to achieve Passivhaus Certification. It is the level of quality control procedures that are considered crucial to closing the building fabric performance gap.

A comparison has also been made between the design intent and the predicted HLC. The results indicate that in the most instances, there is a difference between the design intent HLC and the predicted HLC. For Dwellings 1A, 1B and 2 (all designed to achieve Passivhaus Certification) the design intent is significantly greater than that predicted, in some case by a considerable margin (more than 40% for Dwellings 1A & 1B), suggesting a rather pessimistic design based SAP assessment. Part of the reason for this is the use of much higher U-values in the design based SAP assessment than is required to achieve Passivhaus Certification. The

doorway using an adjustable door frame and panel. The greater the air flow required to maintain a given pressure differential, the leakier the building.

reasons why such U-values were used is not known. In the case of Dwellings 3A and 3B, the opposite is true, where the design intent was significantly lower than the predicted HLC, although to a much lesser degree. This could have important implications in terms of whether the dwellings achieve the required level of compliance or not. A closer examination of the design based SAP assessments reveals that part of the reason for the discrepancy between the design intent HLC and the predicted HLC can be attributed to errors in the data that had been input into the design based SAP assessments. These errors ranged from incorrect dimensional data to errors in the U-values and the U-value calculations. Another factor that will also have contributed to the discrepancy will be changes made to the design during construction.

Errors in the data that is used as input into SAP are not unusual. A study of input errors in the application of SAP for new dwellings found errors in 56 out of 82 assessments (68%), and that when corrected, about 20% of the dwellings failed to meet the regulatory target emission rate (Trinick *et al.*, 2009). In addition, recent work undertaken by the Zero Carbon Hub as part of their *Housebuilding Process Review* found errors in all of the design based SAP assessments that they reviewed (Zero Carbon Hub, 2014). This study, along with the work undertaken by Trinick *et al.* (2009) and the Zero Carbon Hub (2014), highlights the requirement for much greater control of SAP and the need for the development and implementation of a quality control process that will minimise these input errors.

4.2 Results of the coheating tests in context

In order to be able to put the results obtained from the case study dwellings in context, the predicted and measured HLC for the case study dwellings have been compared against the results obtained from 18 other new build dwellings that are contained within the Centre for the Built Environment (CeBE) Group at Leeds Beckett University's coheating test database (see Figure 3). The CeBE Group coheating test database is the largest single database of coheating data in the UK. It represents approximately 10 years' worth of coheating testing and contains data on more than 50 coheating tests undertaken in both new and existing dwellings, all of which have been tested by the same organisation. All of the new build dwellings contained within the database have all been built to comply with Part L1A 2006 (NBS, 2006) as a minimum, vary in terms of age, size, built form and main construction type and broadly encompass the main construction techniques and dwelling forms found within England and Wales. It should be noted that although the CeBE database is the largest of its kind in the country, due to the practical difficulties associated with undertaking large numbers of coheating tests on dwellings in the UK, the numbers of dwellings contained within the database are relatively small and they are not the result of random sampling. In fact, due to the nature of the coheating testing work that has been undertaken by CeBE Group, the database is more likely to be biased towards dwellings that were designed to have a level of fabric performance in excess of the minimum required for compliance purposes alone. Consequently, any inferences made

using the database cannot be qualified as being representative of the UK housing stock as a whole.

An analysis of the coheating data contained within Figure 3 illustrates that not only is there a very wide range of performance within the coheating database, but in all of the new build dwellings tested, the measured performance exceeded the steady state predicted performance. Most importantly, in the majority of the dwellings tested, the 'gap' between the measured and the steady state predicted performance is considerable; in two of the dwellings the difference is more than 100% (see Figure 4). In addition, there are a number of cases where the levels of performance measured are likely to be in excess of that required to achieve Building Regulation compliance. This is likely to have important implications in terms of the energy use and CO₂ emissions attributable to these dwellings and the levels of thermal comfort experienced by the occupants. With respect to the case study dwellings, although the performance of Dwellings 3A, 3B, 4 and 5 should give some cause for concern, they are by no means the worst performing dwellings in the sample. In fact, the data contained within Figure 4 suggests that the performance of these dwellings generally lies somewhere towards the bottom end of the range of the sample. In terms of Dwellings 1A, 1B and 2, Figure 3 illustrates that these case study dwellings are the best performing dwellings in the sample by some considerable margin, both in terms of predicted and measured performance. This is not surprising given that these dwellings were intentionally designed to have a very low predicted HLC, as it is intended that they all be Passivhaus Certified, and have a very small floor area by UK standards.

5. Conclusions

Seven case study dwellings, all designed to Level 4 of the Code for Sustainable Homes or better, have undergone a coheating test as part of the Technology Strategy Board's Building Performance Evaluation Programme. The coheating test was undertaken in order to quantify the thermal performance of building fabric of these dwellings once constructed. Although it is only possible to make a number of qualitative comments, due to the small non-random nature of the dwellings tested, the results indicated that in all of the dwellings tested, a gap existed between the measured whole house heat loss and the predicted steady heat loss. This has implications in terms of energy consumption and CO₂ emissions. Although a gap in performance was measured in all of the case study dwellings, the absolute size of the measured gap varied considerably from dwelling to dwelling, ranging from just over 2W/K to almost 86W/K. If one takes into account the various uncertainties associated with the coheating test, then the size of the building fabric '*performance gap*' that was measured for three of the case study dwellings can be considered to be negligible, indicating that the building fabric associated with these dwellings is performing *in situ* pretty much as predicted. This result is extremely important, as it illustrates that it is practically possible to construct dwellings where the building fabric performs thermally more or less as predicted, thus effectively bridging the building fabric '*performance gap*' that has been found to exist in mainstream housing in the UK.

The results obtained from the case study dwellings have also been compared to a larger new build coheating test dataset. This comparison revealed that although a gap exists between the predicted and measured thermal performance of the building fabric in the majority of the case study dwellings, the case study dwellings are by no means the worst performing dwellings in the sample. In fact, the fabric performance of the case study dwellings is generally very positive, as it lies somewhere towards the bottom end of the range of the sample.

Practical relevance and lessons learned

This paper describes an aggregate approach, a (coheating test), that has been applied to a small number of case study dwellings to determine the thermal performance of their building fabric *in situ*. The results suggest that although a considerable gap in performance can exist, which will have significant implications in terms of energy use and CO₂ emissions, the results also indicate that it is possible to construct dwellings where the building fabric performs thermally more or less as predicted. This result is extremely important, as it illustrates that it is practically possible to bridge the building fabric '*performance gap*' that has been found to exist in mainstream housing in the UK.

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Table captions

Table 1: Details of the case study dwellings.

Table 2: Main construction types and design U-values for the case study dwellings.

Figure captions

Figure 1 An example of the multiple linear regression method of analysis that accounts for the effect of solar radiation on the test data.

Figure 2 Design intent, predicted and measured HLC of the case study dwellings.

Figure 3 Measured versus steady state predicted HLC of the case study dwellings and the Leeds Beckett new build coheating database.

Figure 4 Comparative difference in the measured versus steady state predicted HLC of the case study dwellings and the Leeds Beckett new build coheating database.