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Using In-Situ Building Fabric Thermal Performance Testing to Calibrate As-Built Models of Low Energy Dwellings in the UK

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ABSTRACT: This paper presents the methodology and results of in-situ building fabric thermal testing to calibrate as-built energy models of three low energy dwellings in the UK, so as to examine the gap between the as-designed and as-built energy performance. The in-situ tests included air permeability testing, along with thermal imaging and heat flux measurement. Despite the dwellings being designed to high thermal standards, heat flux measurements showed poor thermal quality of the walls and roof section even for the 'good' quality sections that were measured. Thermal imaging surveys revealed air leakage pathways around door/window openings, penetrations and junctions between walls and ceilings indicating poor detailing and workmanship. Air permeability (AP) was found to have increased after the initial test due to post-completion alteration to the building fabric. Though the results were higher than expected they were within the UK Building Regulations limiting fabric parameters. Calibration of the model through temperature monitoring provided less extreme projected energy performance gap than simply replacing the designed AP values and U-values with test results. Insights from the study have reinforced the need for national Building Regulations to require as-built energy models with in-situ test data to measure the gap between intent and outcomes.
KEYWORDS: Building performance evaluation, performance gap, thermography, energy modelling

1. INTRODUCTION

The UK Government is legally committed to a target of net zero for UK greenhouse gas (GHG) emissions by 2050 and to five-year carbon budgets in the interim set by the Committee on Climate Change [1]. Over the years various policies aimed at encouraging energy efficiency measures in domestic buildings such as Code for Sustainable Homes (CSH) and the Green Deal, have come and gone. According to the UK government's Department for Business, Energy and Industrial Strategy's (BEIS) Clean Growth Strategy [2], the UK has outperformed the target emissions reductions; however, the housing sector, will need to do more to meet its share of reductions.

These carbon budgets have driven the need for new dwellings to be built with high standards of insulation and airtightness with managed ventilation, high efficiency heating systems, and renewables. However, there is a growing concern that low/zero energy dwellings often underperform as compared to the design specifications, due to discrepancy in building fabric thermal performance, systems efficiency and occupant behaviour.

Building performance evaluation (BPE) studies offer a range of methods to evaluate the effectiveness of design and construction in meeting expected performance. Recent performance evaluation studies [3, 4] have demonstrated that in-use energy use can be up to three-five times more than design predictions. This energy performance gap (EPG) between the predicted energy performance of a building (domestic or non-domestic) and its measured performance has been highlighted by several studies [5-14]. BPE studies of new dwellings [7, 14-16] have shown the reasons for performance gap to be related to discrepancies that arise across the building process, from the design and modelling tools used to design the building, through build-ability, materials and build quality (as-designed and as-built), systems integration and commissioning but handover and operation, as well as the understanding, comfort and behaviour of the occupants. Clearly national policy targets for carbon reduction cannot be met without understanding, quantifying and minimising this performance gap between as-designed, as-built and in-use stages.

This paper uses in-situ building fabric thermal performance testing to examine the gap between as-designed and as-built energy performance to create and calibrate as-built energy models of three low energy dwellings in the UK. The study is part of a research project (2015 – 2020), funded by the European Union's Horizon 2020 Research and Innovation programme, called Zero Plus project which seeks to achieve net-regulated energy use of less than 20 kWh/m^2/year. This paper presents the methods used and results of the pre-occupancy evaluation of three dwellings designed to meet the above target.

2. CASE STUDY DWELLINGS

The three case study dwellings in the study (Zero Plus project) are shown in Figure 1 on the following page. The dwellings are located in York (UK). The house numbering is from right to left in the images. ZP1 and ZP2 are both 2-bedroom semi-detached properties, consisting of two stories. These two properties are mirrored, and both share the party wall along the lounge wall. ZP3 is a 3-bedroom, plus study detached property, also with two stories.

Figure 1: Case study dwellings

All three dwellings were constructed to meet Code for Sustainable Homes (CSH) Level 4. Though CSH is no longer a standard used in the UK, it is the standard that was used when the development began design. Even to this day, though CSH has been abandoned, the standard fabric parameters used in the development to meet it still surpass the current UK Building Regulations (BRUKL) limiting fabric parameters (U-values and air permeability) as shown in table 1.

Table 1: Design and regulation fabric parameters

		ZP design	BRUKL
U-values	Wall W/(m^2·K)	0.17	0.30
	Roof W/(m^2·K)	0.16	0.20
	Floor W/(m^2·K)	0.14	0.25
	Party wall W/(m^2·K)	0.20	0.20
	Windows W/(m^2·K)	1.33	2.00
Air perm. (m^3 h^{-1} m^{-2}) @50pa		4.00	10.00

3. METHODOLOGY

The objective of pre-occupancy testing was to check the actual thermal performance of the building fabric and identify any areas of air leakage, thermal bridging or less than adequate insulation in the external fabric. The BPE methods included the use of a *blower door test to measure air permeability*, *heat flux measurement* to measure thermal transmittance (U-value) and *thermal imaging survey* to qualitatively document heat loss.

Air permeability tests were performed immediately following construction (January – February 2019) and again in April 2019. The test was conducted on each of the three dwellings in accordance with ATTMA TSL1 recommendations, using the Blower Door and depressurisation pressures up to 50Pa. All ventilation openings were closed and or sealed with an adhesive membrane. Measurements of air flow rate through the fan of a Blower Door fitted to the front door were recorded with fan speed varied to give pressures of approximately 10 to 60Pa. Calculations were then made to produce a figure for air permeability at a pressure difference of 50Pa.

Thermal imaging was carried out on the 3rd of April 2019 and performed twice for each property, before and during depressurisation. Depressurisation was used to highlight further areas of air leakage. A blower door was used and a pressure of around -50Pa was maintained for a period of 15 minutes before a second thermographic survey was undertaken. A 19^{o}C difference was maintained between interior and exterior except for ZP2 where the heating was not working. In ZP2, temporary convection heaters were installed approximately four hours prior to the survey.

Heat flux plates were installed for 14 days to measure variations in thermal transmittance (U-value) between good and poor areas in close proximity. The detailed test method outlined in International Standard ISO 9869-1 was followed. Wall measurements on ZP1 and ZP3 were on North walls. The roof measurement was done on ZP2 in the first-floor bathroom. The locations for the Heat Flux plates were chosen as places where there were relatively good and poor areas of building fabric in close proximity (following the thermal imaging assessment). Air temperatures were measured in the respective rooms and outside the fabric as near as possible to the same part of the fabric. The heat flux measurement for assessment of thermal transmittance was carried out from 3rd April to 24th April 2020. The process of quantifying the thermal transmittance involves data logging of the temperature on each side of the fabric element and the heat flow through the heat flux sensors. U-Value W/(m^2·K) of a wall is heat flux (in W/m²) divided by temperature difference (K). This is calculated from the average value of heat flux divided by the average temperature difference. Because temperatures and heat flow vary during the test, average values of each parameter need to be taken over an extended test period.

3.1 Energy model calibration

Throughout the design process, dynamic thermal simulation models were developed and maintained using the Integrated Environmental Solutions Virtual Environment (IES VE) suite of software, specifically ModelIT for modelling the external physical characteristics of the dwellings and Apache for setting thermal parameters and running simulations. IES VE thermal calculation and dynamic simulation software was selected since it is an approved industry standard, audited by the Chartered Institution of Building Services Engineers (CIBSE) and the United Kingdom Accreditation Service as well as being an accredited software for producing Energy Performance Certificates (EPCs) by the Building Research Establishment (BRE).

For modelling purposes ZP1 and ZP2 are a single model (semi-detached type), i.e. type 'B3' and ZP3 is a model of the detached type, 'C4'. The models were calibrated following the pre-occupancy evaluation results to observe potential performance gap issues, specifically where the building fabric may be performing differently from as-designed expectations. Two model calibration methods were explored as described below:

Method 1 (M1) - U-values through heat flux measurements: M1 used heat flux measurements and latest air permeability results to calibrate the model by using these values as parameters in the model. The mean of the air permeability results for ZP1 and ZP2, 5.42 m^3·h–1/m^2 at 50 Pa, was used for model B3. External wall thermal transmittance of 0.56 W/m^2K was used for both B3 and C4. This is calculated by taking the 'good' and 'bad' heat flux measurements in ZP1 and using 'good' as 90% of wall and 'bad' as 10% of wall as the 'bad' measurements were at most representative of corners and trim conditions. A roof thermal transmittance of 0.3 W/m^2K was calculated in the same way.

Thermal transmittance = ('good' x .9) + ('bad' x .1)

Some limitations of M1 were as follows: ZP2 had inoperable heating, thereby limiting the temperature difference between the interior and the exterior. Also, the heat flux measurements were only taken on north walls in two instances and a ceiling in one instance. The worst areas were sought out for taking heat flux measurements; therefore, the thermal transmittance results from the assessment may be higher than the thermal transmittance in the dwellings overall.

Method 2 (M2) – U-values through temperature monitoring. An alternate method was explored for contrast. This method used temperature data measured during the summer in ZP2. Though the inoperable heating was problematic for pre-occupancy testing it provided an opportunity to study the dwelling unoccupied and free running for a longer period. As ZP2 remained unoccupied, this dwelling was used to calibrate the model using internal temperature data. Hourly external temperature data from Weather Underground[1] were used to align with external temperatures in the model. Similar temperature patterns were aligned from the same period for the day with the lowest temperature in the model. Observing the lowest temperature is helpful in observing the greatest strain on the external fabric albeit this evaluation was performed in the end of summer/shoulder season (September) and the lowest temperature was 6°C.

As the dwelling was unoccupied, all internal gains from occupant activity were removed from the model, that is, occupant body heat, appliance energy, domestic hot water energy, and lighting energy. In addition, occupant window opening patters and heating patterns were removed from the model.

After the model was revised to mimic the pre-occupancy state of the unoccupied ZP2 dwelling, the thermal transmittance of the exterior walls and roof were adjusted to find the best match using simulated temperature data in the lounge. Two versions of the model were tested:

1. ***Model A*** – all parameters to match fabric details of the pre-occupancy evaluation (see details of method M1).
2. **Model D** – same air permeability as method M1, 'good' heat flux measurement for the roof of 0.19 W/(m^2·K), and external wall thermal transmittance of 0.26 W/(m^2·K) was used. This value was the change variable for finding the match between the monitored temperature data and model temperature data at the lowest point for the space simulated.

1 www.wunderground.com/history/daily/gb/leeds/EGNM/date/2019-9-10

4. RESULTS

4.1 Air permeability testing

The results of the latest air permeability (AP) tests were compared with the test conducted at the completion stage, as shown in table 2.

Table 2: Case study form and air permeability details

	ZP1	ZP2	ZP3
Total floor area (TFA) (m^2)	84.4	84.4	129.6
Envelope area (m^2)	245.8	245.8	321.1
Design AP (m^3 h^{-1} m^{-2}@50pa)	4	4	4
Completion AP (m^3 h^{-1} m^{-2}@50pa)	3.94	3.97	2.77
Current AP (m^3 h^{-1} m^{-2}@50pa)	5.39	5.44	7.53

Interestingly all three dwellings were found to have better AP results than design targets when they were first tested. The current tests showed that none of the three dwellings met the design target of 4 m^3 h^{-1} m^{-2} @50pa, although all dwellings remained within UK Building Regulations requirement of 10 m^3 h^{-1} m^{-2} @50pa. ZP3 had deteriorated most significantly, and it was noted that there were holes in the kitchen wall where waste pipes had been fitted and the gaps around the pipes were not sealed properly. Other areas that had deteriorated included holes cut in the first floor, presumably to trace pipes or cables in the void and not properly filled, and cracks at the edges of the stairs and under the skirtings. These anomalies were re-confirmed in the thermal imaging survey under depressurisation. According to the developer some work had been done on the properties to fix defects between the first and second test.

4.2 Thermal imaging survey

Thermal imaging in all three dwellings showed air leakage pathways around openings and penetrations. Most surfaces were found to have a low thermal index which generally equals high U-values. The most common areas within ZP1 that these types of anomalies were seen were around skirting boards and at the junctions between the ceilings and walls (figure 2). ZP2 showed similar signs of air leakage throughout the property, as well as air leakage around the openable elements especially around doors and windows. ZP3 also showed similar signs of air leakage that was observed within the other two properties. This was mainly seen at the junctions between the ceiling and wall and around external doors.

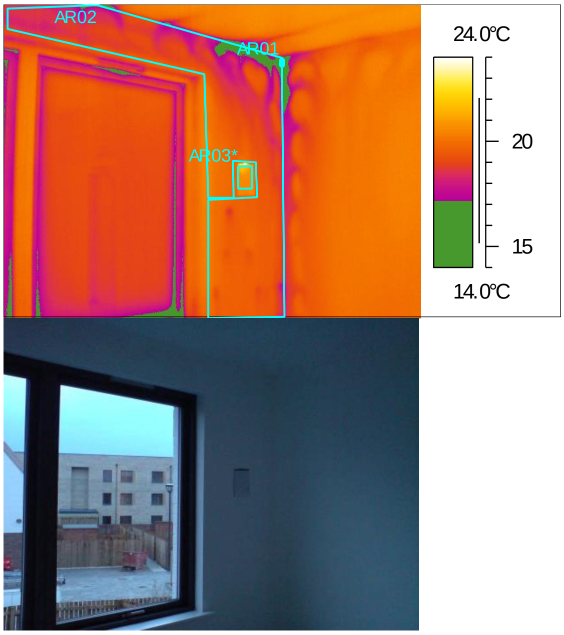

Figure 2: Air leakage in bedroom corner of ZP1

4.3 U-values through heat flux measurements

Overall heat flux measurements showed poor thermal quality of the walls and roof section that were measured. Whereas 'good' and 'poor' quality sections were measured, even the 'good' quality sections did not meet the design U-value. The measured values of thermal transmittance for the walls of the three dwellings were found to be significantly higher than design values as shown in Table 3. In fact, the wall U-values for ZP1 and ZP2 do not meet UK Building Regulations limiting fabric parameters. Similar differences were observed for the designed and measured U-values of the roofs. The U-values as calculated through the thermal imaging were a consistent 0.7 W/(m^2·K); however, well-insulated fabric elements show greater uncertainties in measuring thermal transmittance through thermal imaging. Unfortunately, as the test were taken at a much later stage, the build quality, insulation thicknesses, and actual wall construction could not be reviewed.

Table 3: Heat flux measurements W/(m^2·K)

	Wall ZP1	Wall ZP3	Roof ZP2
Design specification	0.17	0.17	0.16
Measured good area	0.47	0.56	0.19
Measured poor area	1.39	1.95	1.28

4.4 Calibrated energy models

Since in-situ measurements were mainly about building fabric thermal performance that affects space heating, as-designed energy models of the three dwellings were calibrated using the two methods (M1 and M2) to compare the difference between as-designed and as-built (calibrated) space heating energy use.

Using method M1 that used measured U-values (through heat flux measurement) and measured air permeability (M1), as-built space heating was found to be about twice than the designed space heating energy for all three dwellings, as shown in Table 4.

Table 4: Calibration method 1 results

	ZP1/ZP2		ZP3	
	As-designed	As-built	As-designed	As-built
Space heating (kWh)	2,575	5,361	4,491	9,873

Using method M2, thermal transmittance of building fabric elements was manipulated to align the model's internal temperature with monitored data for the lounge. This resulted in an external wall U-value of 0.26 W/(m^2·K) in Model D. In Model A (external wall U-value of 0.56 W/(m^2·K) resulted in 1^{o}C cooler internal temperatures in the model than what was monitored for the same period, which is why Model D was analysed further. In the case of method 2 (Model D), as-built annual space heating energy use was found to be 1.4 times more than designed space heating, as shown in Table 5.

Table 5: Calibration method 2 results (Model D)

	ZP1/ZP2		ZP3	
	As-designed	As-built	As-designed	As-built
Space heating (kWh)	2,575	3,596	4,491	6,002

5. DISCUSSION

The three in-situ tests revealed the magnitude of the gap between expected and actual thermal performance of the building fabric and the likely thermal defects that occurred in the three case study dwellings. Overall, most elements of the wall construction appeared to be well-insulated. However, depressurisation of the dwelling as part of the air permeability test highlighted the air leakage pathways and origins of some of these anomalies. Air movement was prevalent at the junction between walls and ceilings within all three properties, which could lead to thermal bypass. Air infiltration was seen around doors, particularly at the threshold of the doors to the garden area. The heat flux measurement showed areas of the building fabric that did not meet the limiting fabric parameters of Building regulations. It is recommended that the constructor addresses the identified thermal defects before occupants move into the dwellings.

The second wave of air permeability tests showed higher AP values than those conducted post completion as part of compliance testing. This is a significant finding and implies that one-off tests are not adequate to identify thermal defects in dwellings since the building fabric thermal performance may deteriorate as works are undertaken, even after compliance testing. Moreover, there is very little research undertaken on longitudinal testing of building fabric performance; something that needs to be considered in future iterations of Building Regulations. The study has also exposed that communication of design intent amongst developers, constructors and designers is essential for achieving the intended thermal performance. If any works to the building fabric are undertaken (holes cut) following air-tightness testing, professionals responsible for ensuring a continuous air tightness layer must be involved.

Utilising in-situ testing data to calibrate as-built energy models is vital since it exposes the real difference between intended and actual energy performance without the influence of occupancy related factors since the dwellings are un-occupied. This is why calibration of the model through temperature monitoring provided less extreme projected energy performance gap than simply replacing the designed AP values and U-values with results from air permeability testing and heat flux measurements. It is evident that using more detailed data for calibration of energy models reduces the projected energy performance gap. To make this mainstream, future revisions of UK Building Regulations should require in-situ testing of building fabric thermal performance using a combination of tests (and not just air permeability tests), and submission of calibrated as-built energy models for compliance purposes.

6. CONCLUSION

The building fabric thermal performance of three low energy case study dwellings was systematically measured in-situ through concurrent tests involving air permeability, thermal imaging and heat flux measurements. The results were used to calibrate as-built energy models, so as to identify the real difference between as-designed and as-built energy performance.

Despite the dwellings being designed to high thermal standards, heat flux measurements showed poor thermal quality of the walls and roof section even for the 'good' quality sections that were measured. Thermal imaging surveys revealed where the fabric performance was being compromised. Air leakage pathways were found around door/window openings, penetrations and junctions between walls and ceilings indicating poor detailing and workmanship.

Insights from the study have reinforced the need for national Building Regulations to require as-built energy models with in-situ test data to measure the gap between intent and outcomes.

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