

CHECKING “FABRIC FIRST” REALLY WORKS: IN-CONSTRUCTION TESTS USING THERMOGRAPHY

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ABSTRACT

The UK Government strategy for all new homes to be built to zero carbon standards by 2016 is based upon a “fabric first” approach to design. This means prioritising energy efficiency improvements to the building envelope through: increasing overall levels of insulation; reducing thermal bridging; and making buildings more airtight. However, recent research has raised concerns about the standards that are actually achieved in the construction of new housing. More robust quality assurance procedures for construction work may be required to ensure that energy efficiency targets are met in practice. One potential approach is the use of thermal imaging (thermography) to inspect new buildings at different stages during the construction process. The effectiveness of this technique has been tested during the construction of two affordable housing projects in Swansea, UK. Thermal performance issues were identified at both of the schemes, including infiltration through the building envelope and poor insulation of ductwork for mechanical ventilation systems. The results of these two case studies illustrate some practical considerations for the application of the thermography technique and also shortcomings in the current approach to determining compliance with energy performance requirements in UK Building Regulations. This research topic will be of interest to housing developers, built environment professionals, thermographers and researchers interested in methods of investigating the thermal performance of new housing.

KEYWORDS

Thermography, performance testing, construction process, low carbon housing, Building Regulations

INTRODUCTION

In the 'Building a Greener Future' policy statement of 2007, the UK Government announced proposals for all new homes to be built to “zero carbon” standards by 2016 [1]. These standards are to be based upon a “fabric first” approach to design, which means prioritising energy efficiency improvements to the building envelope through: increasing overall levels of insulation; reducing thermal bridging; and making buildings more airtight [2]. As the UK construction industry moves towards full implementation of the 2016 zero carbon target, a series of small-scale research studies have raised concerns that significant discrepancies can exist between the predicted energy performance of a new home as calculated at the design stage compared to the actual performance of the completed building – with evidence of significant under-performance in some cases [3]. This phenomenon is widely referred to within the industry as the “performance gap”. The extent of concern is such that, in a recent consultation on changes to Building Regulations in England, the Government acknowledged

that “the risk of wider scale underperformance cannot be ignored and that the potential performance gap could be very significant” [4].

The main focus of this paper is the relationship between construction quality and performance testing in the delivery of low carbon homes in the UK. Specific consideration is given to the use of thermography as a quality control test for fabric energy efficiency and quality of workmanship during the construction of new housing. It is proposed that conducting tests at appropriate points during the construction process (or ‘in-construction testing’) will help support the management of construction quality and increase confidence that design targets for thermal performance will be achieved in practice [5, 6]. Moreover, it is advantageous if defects can be identified through testing within a reasonable timescale prior to completion, since remedial work can become increasingly costly and disruptive once a building is occupied. The practical experience of the authors has shown that some specific considerations apply to conducting thermographic surveys on a construction site. However, a literature review has identified a lack of detailed guidance on the effective application of thermography in this context (e.g. [7–12]). Having identified this gap in existing knowledge, an approach has been developed for in-construction tests using thermography. The main elements of the testing approach are shown in Figure 1 below.

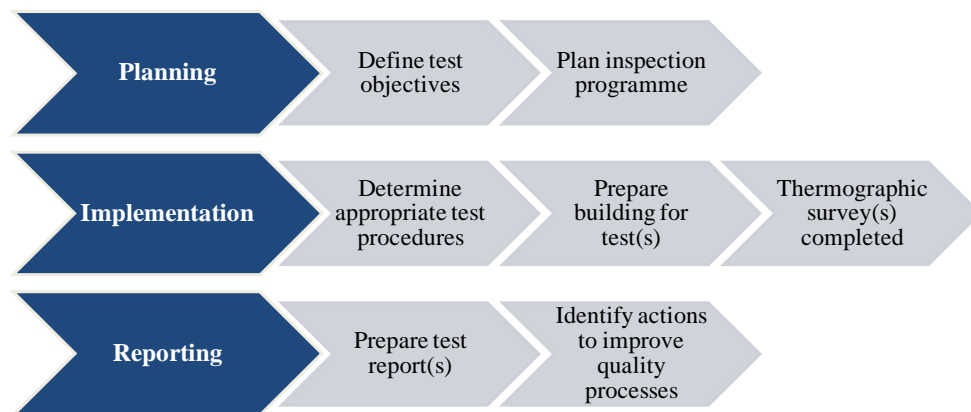


Figure 1. Main elements of the testing approach.

The content of the paper is organised into three main sections as follows:

1. Performance testing and UK Building Regulations
2. Examples of construction defects detected using thermography
3. Introduction to testing approach

PERFORMANCE TESTING AND UK BUILDING REGULATIONS

Levels of compliance with energy efficiency requirements are reportedly a “weaker area” of UK Building Regulations [13]. A report commissioned by the Department for Communities and Local Government ‘Performance Testing of Buildings’ [14] reviewed the scope for additional performance tests to check compliance with the requirements of the Regulations. The report concluded that: “*To be useful, pre-completion performance tests must be quick and inexpensive. They must not delay occupancy, or have to be carried out after occupancy when they may become impracticable*”. In a previous publication, Taylor et al. [5] argued that the 2016 zero carbon target will likely result in a significant shift in the procedures and practices of Building Control¹ and, furthermore, that new approaches to testing in-situ performance

¹ In the UK, Building Control Bodies have the responsibility for checking compliance with Building Regulations.

would need to be developed. In the next section of the paper, this argument is developed further with reference to two case studies where in-construction thermography tests revealed performance defects in low carbon housing projects. The tests conducted at these case studies illustrate the limitations of pressurisation testing as a means of verifying that construction quality is consistent with the predicted energy performance of a building.

EXAMPLES OF DEFECTS DETECTED USING THERMOGRAPHY

Case Study A test results

The environmental design strategy at Case Study A (a block of 69 flats in timber frame construction) was developed with an assumption that the building would be constructed to high standards of airtightness (achieving an air permeability of $3.0 \text{ m}^3/\text{h.m}^2$ at 50Pa). To determine if this level of performance was likely to be achieved in practice, one of the flats in the development was brought to a more advanced stage of completion so that a pressurisation test could be carried out at an early stage of the construction process. The result of this test showed a measured air permeability of $1.09 \text{ m}^3/\text{h.m}^2$ at 50Pa had been achieved – a significant improvement on the design target. However, masking tape was used extensively to seal around openings and sockets prior to the pressurisation test. The use of temporary seals in this way is not permitted according to the testing protocol that is specified in the Building Regulations: “*All external doors and windows should be closed (but not additionally sealed). This includes door thresholds*” [15]. A thermographic survey of the flat 14 months later showed extensive air leakage around the balcony doors as shown in Figure 2 below.



(a) Photograph taken of balcony doors in living room of test flat at time of thermographic survey



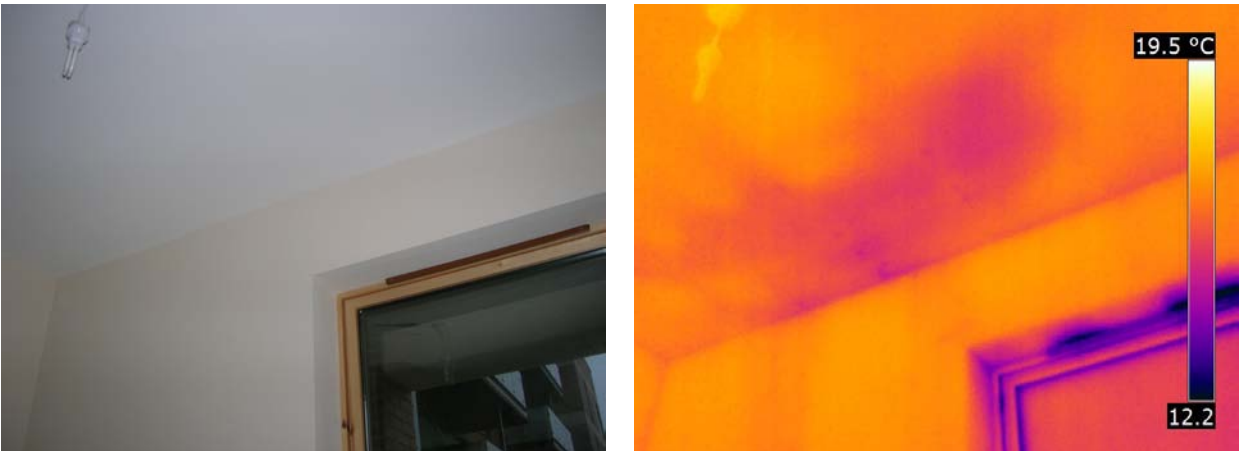
(b) Thermal image of balcony doors corresponding to photograph (a)

Figure 2. Thermal images of flat in Case Study B.

The masking tape applied around the balcony doors before the pressurisation test effectively concealed these locations of air leakage². On this basis, the pressurisation test result is unrepresentative of actual performance and higher levels of infiltration may mean that the energy performance of the flat is less than predicted. The wind pressures that caused the air leakage observed in Figure 2 can also result in other types of heat loss. In the same flat, a thermographic survey indicated a localised surface temperature decrease in the ceiling of one of the bedrooms. The area of the ceiling where this was observed corresponds with the location of an extract duct for the mechanical ventilation unit. It follows that a possible

² It should be further noted that the pressurisation test was not performed as part of mandatory testing and the test result was not used to determine compliance with Building Regulations.

explanation of this thermal pattern could be wind penetration above ceiling level around a poorly-sealed or damaged duct air terminal. This type of defect would contribute to heat loss but does not constitute an infiltration mechanism. It would therefore not be detected by a pressurisation test (this is also the case for thermal bypass caused by “wind-washing” [16]).



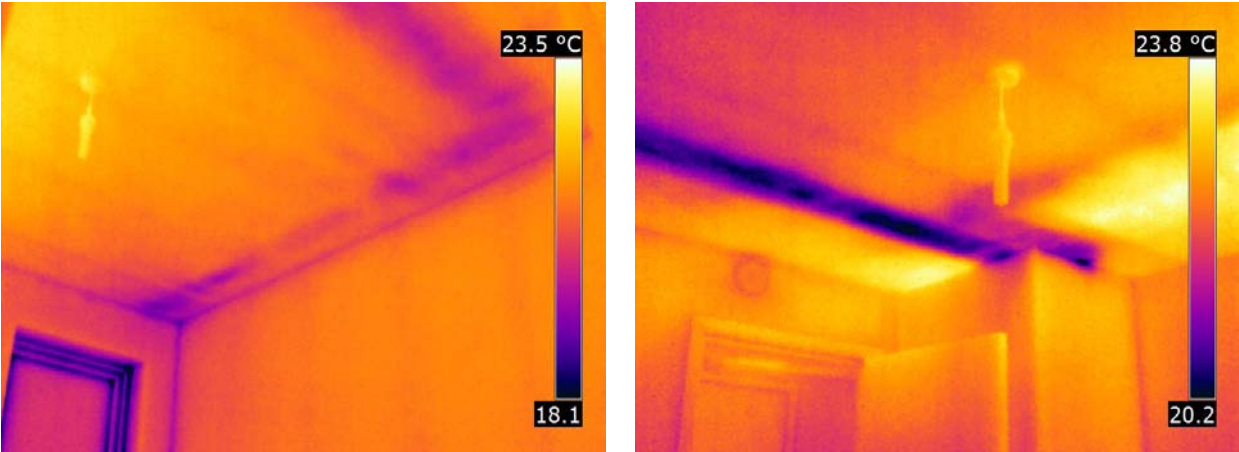
(a) Photograph taken of the junction between the wall and ceiling above a window in one of the bedrooms of the test flat

(b) Thermal image shows localised surface temperature decrease in ceiling area corresponding with the position of the extract duct for the mechanical ventilation unit

Figure 3. Wind cooling effect observed in ceiling below mechanical ventilation extract duct.

Case Study B test results

At Case Study B (a block of 32 flats, part new build and part refurbishment) the ventilation strategy utilised mechanical ventilation heat recovery (MVHR). A thermographic survey in one of the top floor flats indicated that the inlet duct for the MVHR unit was not correctly insulated as shown in Figure 4 below. Poor installation of the MVHR ductwork will reduce the energy performance of the dwelling.



(a) The reduced surface temperatures along the ceiling follow a linear pattern corresponding with the position of the MVHR unit ductwork

(b) The MVHR unit is located in a storage cupboard adjacent to this corner of the room

Figure 4. Insulation not continuous around MVHR ductwork.

Summary of case study results

The case study results illustrate how thermography can be used to identify: air leakage around window and door openings; wind penetration through the external leaf, or “wind-washing”; and poor insulation of ductwork. In these cases, low standards of workmanship and poorly

performing building components were not identified by pressurisation testing. At Case Study A the effect of air leakage around window and door openings would not have been measured by pressurisation testing because the preparation of the building deviated from standard test protocols. Although one example cannot be considered representative of wider industry practices, it does indicate the sensitivity of pressurisation test results to correct site test procedures. The risk of making unrealistic assumptions about the airtightness of the building envelope based upon a pressurisation test result is not only important in the context of demonstrating compliance with Building Regulations – it also has implications for the design of heating and ventilation systems. This emphasises the importance of a holistic approach to environmental design; encompassing design, construction and maintenance practices. For designs that include provision for passive means of ventilation, current approaches to performance testing could be extended by carrying out pressurisation testing with vents sealed and then repeating the test with vents open to calculate an in-situ ‘equivalent area’ of the open vents. This approach could be used to verify design assumptions for background ventilation rates [14].

IN-CONSTRUCTION TESTS USING THERMOGRAPHY

The testing approach follows a process illustrated in Figure 1 comprising three main stages: planning, implementation and reporting. The main purpose of in-construction testing using thermography is to assess the continuity of insulation and identify air leakage paths in the test building. The testing approach is generally consistent with the requirements of BS EN ISO 13187:1998 for simplified testing with an infra-red (IR) camera [10] and is intended to be applicable to all dwelling types. However, practical experience has shown that some specific considerations apply to conducting tests effectively during the construction process and this is reflected in the test procedures outlined in the following sections of the paper. Firstly, it is useful to outline some general principles which help to determine the most appropriate approach to testing:

- **Location of insulation layer(s) within the building structure**

For assessing the continuity of insulation, it will be advantageous if the insulation layer is positioned close to the surface of the construction that is being inspected. Defects within the insulation layer will have two effects when the building is heated: increased heat loss and reduced internal surface temperatures [17]. This localised decrease in surface temperature is the basis on which defects can be identified using thermography. A defect appears more obvious during a thermographic survey when the insulation layer is located closer to the inspected surface because the contrast between the thermal pattern of the defect and the surrounding structure is enhanced. To verify that the insulation layer has been correctly installed, it follows that the optimal time to survey the building is once the insulation layer has been fixed and covered over, but before any finishes have been applied. Surveying the building at a later stage of the construction may involve additional re-work if partial deconstruction is required to repair a defect.

- **Completion of airtightness layer during the construction process**

The airtightness of the building envelope is ideally tested early once the build has been completed up to the airtightness layer and windows and doors are in place (or at least can be temporarily sealed) [18]. Thermography can be used to identify the location of leaks within the envelope if testing is carried out in conjunction with a fan pressurisation test. It may also be useful to conduct tests when the building is exposed to strong prevailing winds (without mechanically pressurising the building). In this case, wind pressures will cause air movement through any leaks in the envelope and it may also be possible to observe “wind-washing”

effects. Testing under these conditions may enable the identification of defects that are more significant in terms of the actual performance of the building in use.

Planning

Certain forms of construction will be more amenable to thermographic testing. This is illustrated with reference to three external wall construction types given in Table 3 below. These forms of construction were selected on the basis that they have been developed to reflect good practice in fabric energy efficiency and represent the main construction types often specified in UK housing.

Construction type	Type code	Description
Timber frame	TF01	140mm fully filled timber frame, sheeted externally, air barrier/vapour control layer and insulated lining internally. Service void and plasterboard. Clear cavity with brick outer leaf.
Cavity masonry	MV01	100mm block inner leaf internally plastered. 150mm fully filled insulated cavity. Brick outer leaf.
Light steel frame	SF01	70mm fully filled light steel frame, sheeted both sides, air barrier/vapour control layer. Service void and plasterboard. Partially filled insulated cavity with brick outer leaf.

Table 1. Energy Saving Trust Enhanced Construction Details [19].

- Timber frame external walls (TF01):** An initial thermographic survey to check the continuity of insulation would ideally be carried out once the insulated lining is fixed to the timber frame (enclosing the insulation between the studwork). The purpose of this initial survey would be to confirm that the insulation between the studwork has been correctly installed before the insulated lining is covered over with plasterboard. Either an internal or external survey would be effective for this first test. However, an internal survey is likely to be more appropriate since it allows greater flexibility with respect to the timing of the test³ and the external envelope may also be obscured by scaffolding. At this stage of the construction process the building heating systems would not have been installed and commissioned and so an alternative method of heating the building would need to be adopted for the test. A second survey would usefully be carried out in conjunction with a pressurisation test to identify locations of air leakage through the building envelope once the heating, plumbing and electrical services have been installed (to check the effectiveness of sealing around the building services).
- Masonry Cavity external walls (MV01):** An initial thermographic survey to check the continuity of insulation within the cavity is ideally carried out once the building is weathertight but before a parge coat is applied to the internal face of the inner leaf. Either an internal or external survey would be effective for this first test. If any defective areas of insulation are identified then repair work may necessitate partial deconstruction of the inner or outer leaf. A longer heating period would be required in comparison to the testing of timber frame structures because of the thermal mass of the block inner leaf. Once the plasterwork has been applied to the internal leaf (this effectively acts as the airtightness layer), a second survey would be usefully carried out in conjunction with a pressurisation test to identify air leakage.
- Light steel frame (SF01):** As with the timber frame external wall type, an initial survey would ideally be carried out to check the continuity of insulation between the studwork once the sheeting has been fixed to the internal face of the steel frame (before it is covered over with plasterboard). Thermography will be less effective for checking the continuity

³ The best conditions for external surveys are found during the night, sometime after sunset, when the effects of direct solar radiation on the surface temperature distribution of the external envelope can be discounted.

of the insulation within the cavity since any discontinuities in this insulation layer will be difficult to detect from either an internal or external survey. This is because the intermediate layers of the external wall structure will reduce the effect the defect has on the internal and external surface temperatures. In this case, supervision of the construction process becomes increasingly important to ensure the insulation is securely fixed back to the inner leaf to prevent air from circulating around the insulation. A second survey would usefully be carried out in conjunction with a pressurisation test to identify air leakage.

Implementation

The interpretation and reliability of thermographic testing is facilitated by a stable pattern of heat flow through the building envelope and a sufficiently large difference between internal and external temperatures so that surface temperature variations are detectable. Pearson [8] recommends a minimum temperature difference of 10°C between internal and external temperatures for thermal performance surveys. Wahlgren & Sikander [18] state that a temperature difference of at least 5°C is acceptable for surveys to identify air leakage. Prior to testing, the building may be heated using either electrical fan heaters, radiant heaters or the building heating system (if this has been installed and commissioned). A decision tree for selecting the most appropriate approach is given in Figure 5 below. However, experience indicates that a useful daytime temperature difference can be obtained through solar gain alone for internal surveys and thus in some circumstances it may be possible to identify defects in the building envelope without providing supplementary heating.

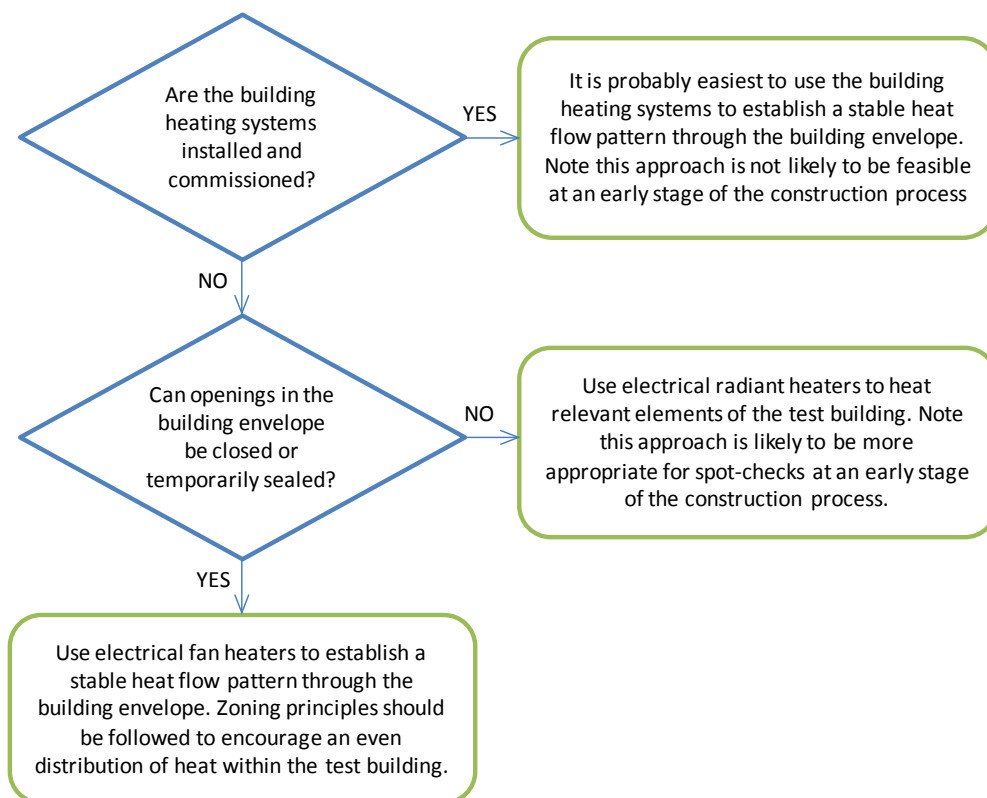


Figure 5. Decision tree for selection of heating method.

In outline, testing consists of two stages as follows:

- **Pre-test requirements:** to prepare the building for testing, including a walkthrough of the test building and the installation of heaters and other equipment (if required).

- **Site test procedure:** the process of examining thermal patterns on the internal and/or external surfaces of the test building.

The **pre-test requirements** are as follows:

1. Select a heating approach using the decision tree in Figure 5.
2. It is preferable to commence heating of the test building at least 24 hours before the inspection. However, a shorter heating period may be adopted if it is not possible to obtain access or permission to operate the heaters outside of normal site working hours. In this case, the number and/or power output of heaters may need to be adjusted to compensate for the reduced heating period.
 - If using electrical fan heaters:*
 - Install 110V electrical fan heaters in the test building⁴. The power output and number of heaters required will depend upon the configuration of the building. The placement of circulation fans in appropriate locations to encourage air movement may assist with achieving a more even temperature distribution.
 - If using electrical radiant heaters:*
 - Install 110V electrical radiant heaters in the test building. It may be necessary to adjust the distance of the radiant heater from the target building element and also the angle of inclination of the heater element to the building surface to achieve an even heating profile. The IR camera can be used to assist with this process. Care should be taken not to point the IR camera directly at the radiant heater when it is switched on as this may damage the detector.
 - If using building heating systems:*
 - Adjust the heating controls in the test building according to the instructions provided by the manufacturer.
3. Prior to switching on the heaters, all external doors, windows and trickle vents should be closed. Internal doors should be fully opened and restrained (if necessary) to encourage an even distribution of heat within the test building.
4. If the inspection personnel are on site before the heaters are to be switched on then this may be an appropriate point at which to conduct a walkthrough of the test building. The walkthrough presents an opportunity to record visual images, taking note of any factors that may influence heat flow through the building envelope (e.g. service penetrations), and review health and safety issues with the site manager and/or other responsible person(s).
5. If a meteorological station is located in close proximity to the test building then this may be a convenient way of noting the local weather conditions during the 24 hours preceding the survey. Temperature and humidity sensors may also be installed in appropriate internal and external locations if required. All surfaces to be inspected during the survey must be dry and therefore any precipitation in the 24 hours preceding the survey is likely interfere with surveys of the external facade of the test building.

The **site test procedure** is as follows:

1. The external air temperature, external relative humidity (RH) and wind speed should be recorded at the start of the survey using a suitably calibrated environment meter (with thermometer, hygrometer and anemometer functions). The air temperature and relative

⁴ Note the Health and Safety Executive (HSE) recommends a reduced low voltage 110V supply system for all portable electrical equipment used on construction sites in the UK. Further information is provided in BS 7375:2010 Distribution of electricity on construction and demolition sites – Code of practice.

humidity inside the test building should also be recorded. Ideally, these measurements should be repeated at the end of the survey.

2. Thermal patterns should be examined using the IR camera on the internal surfaces of the test building and/or all aspects of the external facade (unless radiant heaters are used, in which case only the relevant element of the building envelope need be inspected). Particular note should be taken of windows and any joints in the construction (e.g. wall-ceiling junctions). Any areas of special interest and any thermal irregularities should be studied in detail. Written or audio notes should be taken to accompany the thermal images recorded during the inspection to aid the interpretation of results.

Reporting

The results of the survey should be presented in a report including a description and interpretation of the thermal images recorded during the survey, and preferably accompanied with corresponding visual images. Recommendations for the detailed content of the report are given in Pearson [8] and BS EN 13187:1999 [10].

CONCLUSIONS

The UK Government expects carbon savings to be delivered by increasing the energy efficiency of new housing to zero carbon standards. However, a growing body of evidence for a potential “performance gap” suggests that planned carbon savings may not be delivered in practice. Underperformance poses a reputational risk to the UK construction industry, as Government carbon reduction targets may be undermined and householders may not benefit from the expected savings in their energy bills. This paper has developed an argument for extending current industry practices for in-situ performance testing of new housing to help address these risks. A testing approach using thermography to check the continuity of insulation and locate air leakage in the building envelope is outlined in the paper. Existing literature on thermography does not provide detailed guidance for the effective implementation of testing during the construction process. The testing approach, which is being developed as part of a PhD research programme at Cardiff Metropolitan University, seeks to address this gap in existing knowledge. The main benefit of ‘in-construction testing’ is that defects can be identified at an early stage of the construction process when it is likely to be easier and less costly to carry out any remedial work that may be required. Therefore, thermography is potentially a useful complement to pressurisation testing, and the use of both techniques together could provide a more representative assessment of fabric energy efficiency and quality of workmanship in residential construction projects.

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