Building Performance Assessment Protocol for Timber Dwellings – Conducting Thermography Tests on Live Construction sites

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Abstract. This paper introduces the pan Wales (UK) Home Grown Homes (HGH) project (2018 and 2020) which focusses on three areas of improvement for delivering high performance, affordable and healthy homes. The HGH project is funded by Powys County Council, through the European Regional Development Fund's Agricultural Stream. The HGH project is being delivered by Woodknowledge Wales in a consortium with Cardiff Metropolitan University (CMU), TRADA and Coed Cymru, with seven work packages. 'More & Better Homes from Wood' (work package (WP) WP3) focusses on the assessment of building performance for dwellings using timber, and is being delivered by a multi-disciplinary team at CMU through the Sustainable and Resilient Built Environment group (SuRBe). This paper discusses the context and need for the HGH project as Wales launched its low carbon agenda in March 2019. The focus for the paper is to introduce the building performance assessment (BPA) protocol to be implemented by SuRBe across several housing case studies in Wales, through the design, in-construction and occupancy phases, to address thermal and fire (TaF) performance issues, and impacts upon occupant quality of life, comfort and safety. Preliminary results are presented of in-construction testing on a live construction site with the challenges of conducting thermography tests whilst construction progresses and the weather becomes warmer in April 2019. This paper will be useful for academics, architects, building contractors, housing developers and professionals undertaking building performance assessment and evaluation on live construction sites.

Keywords: Building Performance Assessment, Dwelling, Timber, Wales; the Performance Gap; the Safety Gap; Construction.

1 Introduction

This paper introduces the HGH project, WP3, and the building performance protocol being adopted as part of work on housing case studies across Wales. The main aim of this protocol is to gather evidence with a methodology that can be replicated and validated as it is undertaken in live construction sites. The suitability and reliability of in-construction tests are evaluated. This article describes the development of the protocol, the main concepts behind it and provides a case-study to exemplify the challenges, advantages and limitations of investigations of this nature. The objective is to contribute towards the improvement of buildings, in order to tackle issues related to the Performance Gap and the Safety Gap, and consequently improving the efficiency of buildings' and occupants' safety and well-being.

2 The need for building performance assessment of timber dwellings

2.1 Context to Wales and the need for low to nearly zero carbon dwellings

Since 2008, the Climate Change Act has been a relevant part of the UK's commitment to develop a number of strategies towards reducing greenhouse gas (GHG) emissions [1]. The established targets (in 2008) were to achieve at least 34% GHG reduction by 2020 and 80% by 2050, against 1990 baseline [1, 2]. The energy use in the residential stock account for more than 25% of energy use and CO2 emissions in the UK [1, 2]. As it was eloquently described in the "Farmer Review – Modernise or Die" [3], as the UK Government plays an active role towards the development of better new homes, it has the potential to influence the way buildings are delivered [3]. This can be better achieved by having clear and transparent mechanisms in place, to ensure the quality of the end-product (buildings). This process will create a long term sustainable construction industry and will have quantifiable benefits in terms of productivity, quality and efficiency [3]. More recently, in February 2019, a publication by the Committee on Climate Change (CCC) and its Adaptation Committee [I] reported that "UK's legally-binding climate change targets will not be met without the near-complete elimination of greenhouse gas emissions from UK buildings" [4].

Therefore, it is evident that there is a significant need to increase the quality and efficiency of dwellings in the UK. Research evidence supports the need for clearer methods towards truly achieving better buildings in a more transparent manner [5]. The construction industry should follow specific practices that will help not just to 'aim' to achieve better quality of buildings, but to 'ensure' high standards and that truly efficient and safe buildings are being delivered. This could be achieved by having further mandatory compliance tests to ensure that buildings are safe and efficient [5], i.e. in terms of fire safety as well as thermal efficiency, this will also help to reduce fuel poverty and increase quality of life of residents.

In 2017, the Welsh Government (WG) (Wales is one of four sovereign states with some unitary authority in the UK) introduced the Innovative Housing Programme (IHP) [6]. The IHP funding is aimed at helping to incentivise further research towards increasing locally sourced timber construction, by investing in local resources, skills and industries [6]. The HGH project is an example of this investment. Furthermore, by 2020, the WG's target for new affordable dwellings is 20,000 and traditional forms of construction with brick/block exterior walls are both unsustainable from a materials and climate change perspective, but are also slow to construct compared with timber construction [7].

2.2 Context to the Performance Gap and the Safety Gap

One of the greatest problems of new housing is the performance gap, where defects in the construction process can impact upon thermal performance and operational energy use for heating once occupied; a major finding of the UK Government's Building Performance Evaluation programme in 2016 [8, 9]. There is significant and compelling evidence of the existence of the Performance Gap in buildings and its impact upon the energy efficiency of dwellings and thermal comfort [10, 11, 12, 13]. The Performance Gap can be described as the "discrepancy between the measured and the theoretical energy performance" [13], also described as "a 'Knowledge Gap' between off-site designers and on-site constructors and within both the policy makers and administrators, including local government building control officers" [5]. There are many factors inducing the presence of the Performance Gap in the building industry, some of these factors are the inconsistencies in test guidelines, financial pressures, time constrains that lead to short term fixes [5] as well as the lack of compulsory monitoring standards, particularly at the construction stage, where many issues can be concealed.

Littlewood has gone a step further and identified and entitled a Safety Gap' [5, 14-16], and through his work co-funded by Sustainable Construction Monitoring and Research Ltd, and Cardiff Metropolitan University (CMU) he has developed and implemented a non-destructive building fire safety assessment, measurement and reporting protocol that illustrates where the construction process and products can impact upon inadequate fire safety performance, particularly with a lack of or inappropriate fire stopping and compartmentation. Problems with passive fire protection measures were demonstrated catastrophically in 2017 by the Grenfell Tower tragedy [17]. In 2019, The UK Fire Industry Association (FIA) highlighted that close to 40% of all new homes built in the UK are unsafe with zero fire stopping installed to prevent the spread of fire, smoke and toxic gas [18]. These issues are creating significant concerns regarding the safety of new build homes. Therefore the imperative importance is to find solutions to these two significant issues: the Safety Gap and the Performance Gap, or thermal and fire performance (TaF) [19], which are in many cases linked by unwanted air leakage pathways inherent following inadequate workmanship on site. TaF performance is being investigated by the CMU's team as part of their contribution to the HGH project, which commenced in April 2018.

3 Methodology

3.1 Work Package (WP) 3: More and better homes

The BPA protocol for the HGH project are discussed below, and covers the design, in-construction and operation phases for timber dwellings in Wales, which has been developed and is to be implemented as part of WP3 'More and Better Homes from Timber'. WP3 aims to develop, enhance and prove the business case for timber construction, including offsite manufacturing (OSM) with particular attention on architectural technology and building fabric performance. Its focus is in supporting a number of active housing projects with local authorities, housing associations and housing developers by proving guidance on how to assess building performance and impacts upon occupant safety and wellbeing, through design, construction and occupation. This is to help clients understand the role of building performance in the procurement of future housing projects and ultimately in developing better, more energy efficient and healthier and safer homes. In doing so the HGH project will be able to establish the value of this kind of assessment and the challenges in carrying it out, and as such complements the WG's Innovative Housing Programme (IHP) since it undertakes building performance assessment during the design stage and also the construction stage on site, with a focus on thermal and fire (TaF) performance; and the habitation stage focused on occupant wellbeing and comfort. The focus of the IHP project's [20] building performance monitoring will be primarily energy focused (but in May 2019 this has not as yet been tendered for delivery). So both projects are mutually beneficial to clients, their design teams and dwelling occupants.

The brief description of the different research practices and processes described in the BPA protocol developed by the CMU team based on their previous experience that is being used in the HGH project, are summarised here. At the design stage: dynamic thermal modelling (3D) and thermal bridge analysis (2D). At the construction stage - in-construction testing: Littlewood's Smart Fire Performance Test to prevent the Safety Gap; Thermography for assessing the fabric thermal performance; and Air Permeability Tests. At the operation stage: Occupant Interviews with short form (SF)-36 Questionnaire and diaries to measure well-being and quality of life. This BPA protocol aims to assist parties involved at any stage of the construction process, in order increase the efficiency and quality of buildings. This will be achieved by following a series of exploratory processes that contributes towards a better understanding of the individual buildings and their elements. As a result, it is aimed to further identify and collate evidence on the issues at the design and construction stages that impact upon the Performance and Safety Gaps, and as such occupant quality of life.

Assessing thermal performance during the construction process was first developed by Littlewood in 2009, as part of a suite of tools known as in-construction testing (iCT) to assess workmanship defects on construction sites, which if present could be rectified before completion [1]. In 2019, iCT is being used to assess both thermal performance and also fire performance, and the next section of the paper discusses a case study in the use of thermography known as an iCT_Th test.

3.2 Building Performance Assessment (BPA) protocol – in-Construction Testing: Thermography iCT_Th

Thermography is "the science of acquisition and analysis of thermal information from non-contact thermal imaging devices" [21]. Thermal 'information' is captured by an infrared (IR) camera, by measuring the intensity of IR radiation emitted from the surface of the object under observation. An IR camera is adjusted by the operator to convert the measured intensity of infrared radiation emitted by an object into a surface temperature (these adjustments compensate for the material and surface properties of the object and the environmental conditions in which it is observed). Hence, the resulting thermal image provides a two-dimensional map of temperature difference over the surface of the object. Thermography is an established technique within the construction industry for checking the continuity of insulation, identifying sources of air leakage, thermal bridging, workmanship, detecting and mapping moisture in a building [22]. The output when using an IR thermal camera is a thermogram, which illustrates hot and cold areas as different colours [23]. In most instances qualitative thermographic building surveys provide sufficient information, for example to identify: sufficient, correctly installed and thereby continuity of insulation; occurrences of thermal bridges; sources of air-leakage, particularly at critical construction junctions; moisture and damp within an element; hidden components, such as pipes and wall ties; and electrical faults [24, 25]. As a minimum prior to an iCT_Th test the developer and building contractor are asked information, as follows. Client: drawings, building plans, sections and elevations, construction details, including 2D/3D models (BIM) if available.

Details of location, altitude of the building; specification of materials, heating and ventilation systems; availability for meetings. Building Contractor: Details of the type of insulation, external cladding; facilitating access on site in a safe and efficient manner; suitable access to electricity supply, i.e. transformers, extension leads; occasional observation of the heaters to make sure they remain activated for eight hours prior to the test; collaborating with the research team to some extent, to ensure that the test can be carried out, i.e. helping to ensure that the equipment can be safely installed and researchers can gather the necessary data and undertake the necessary test under specific conditions required for the test. The iCT_Th test process includes three stages, a pre-test, on-test and post-test, each process is discussed in more detail here [1] but is summarised next. The pre-test process is undertaken a couple of weeks before the actual test and includes a walk-around site to determine the test dwellings, meeting and discussing the test with the construction staff and if they have identified any particular issues that they would like explored during the test. In addition, the pre-test phase is to identify any issues with supply of power and locations of transformers and cable lengths, or gaining access to the test dwellings after sunset in terms of trip hazards that could impact upon health and safety and so in essence this is part of a risk assessment.

The case study presented in this paper is a pilot study for the implementation of the construction stage assessment using the BPA protocol and thermography, iCT_Th. The aim was three-fold, one to assist the developer and building contractor understand whether there were inadequate workmanship issues in the test dwelling and secondly for them to understand what is required for a thermography test and the limitations in April in south Wales (related to weather and hour of day for the test). Thirdly, to gain an appreciation by the researchers of working together and also the challenges of conducting a thermography test on a live construction site, and with varying weather conditions. The case study building uses an OSM timber frame system for exterior walls and includes five blocks of four floors, of either one or two bedroom apartments. The construction site is located in Cardiff, Wales and has been in progress for approximately six months and is due for completion at the end of 2019. The initiation of the iCT_Th test process was commenced in March 2019 and took until the 16th April 2019 to be completed. As part of the pre-test process the researchers conducted several visits to the construction site to identify the test dwellings, location and availability of power and the equipment needed to pre-heat the one bedroom flats - in order to record a delta-T of 10 degrees Celsius (ºC)(as recommended by Pearson [26]). The equipment used for the test was a thermal camera, heaters, and extension cables. The day of the test took several days and weeks to arrange due to unexpected instances on site, see discussion section below. In addition, the weather patterns during spring can be unpredictable in the UK and with daylight saving coming to an end on the 31/03/19, this meant that the minimum time to commence an external iCT_Th was delayed until 21.00 (one hour after sunset).

4 Results – iCT_Th

On the day of the iCT_Th test unfortunately during the day the weather changed and rain started, which precluded an external test (to some relief of the site manager who was due to remain at work until 22.00). An internal iCT_Th test was undertaken in one flat as the building in question restricted the use of two (connected) 110 volt/32 amp extension cables connected to a transformer on the ground floor (a consideration when the flat on the first floor). Whilst, the team have two 110v/32a electric heaters, without a splitter (an electrical socket with one male 110v/32a connection and two female 110v/16a connections) it was only possible to connect one 110v/32a 3kilowatt heater). Ideally, following Pearson [26] the heater would have been activated 24 hours prior to the iCT_Th test. However, since the building is timber frame, and due to fire safety regulations, and as there is no site personnel on site between 18.00 and 07.00 the next day, it is not permitted to leave any electrical heating devices unattended between these hours. So the heater was activated by one of the researchers at 07.30 on the test day, and verified as being working by the site manager at various times during the day. The environmental conditions measured during the test are listed here. External and internal temperature and relative humidity-15.4^{0}C/52.7% and 23.6^{0}C/55.5%. The Delta T was not ideal at 8°C, however as Hopper et al [27] have reported results that can still be evidence with a Delta T limited to 5°C. This is one of the challenges of conducting iCT_Th tests when balanced against weather patterns and availability of case studies for testing. The analysis of thermograms considered this issue in our margin of error.

During the iCT_Th test both thermograms and digital images were captured simultaneously with the Flir E60 camera and also images with a digital camera; in order to analyse the performance of the test dwelling currently under construction [28]. One of the most significant difficulties during this test was the material of the insulation, since it was still fully exposed. The surface of the insulation was finished with a highly reflective material, which hindered the quality of the thermograms. It is noted that materials with high emissivity values have a low reflectivity, and materials with low emissivity have a high reflectivity [21]. When conducting thermography tests, only materials with high emissivity provide reliable readings; since materials with low emissivity tend to reflect the temperature of surrounding objects and materials [26]. Thus, materials with low emissivity can produce misleading results; with can have disastrous consequences when reporting on what appears to be poor quality [27].

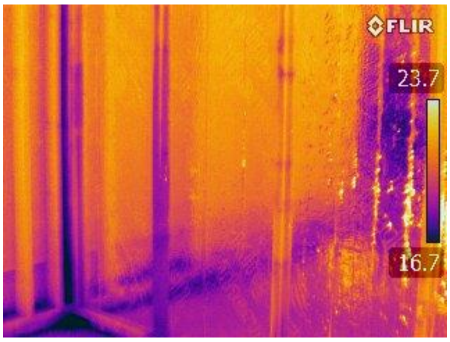
Fig.1 illustrates below some of the thermally tuned thermograms and digital images from the test dwelling.

Figure1. Digital images and thermograms.

1st floor apartment – Internal view of external wall, North Façade (Bedroom)

Digital Image 1 illustrates the corner of one of the external walls which is North facing.

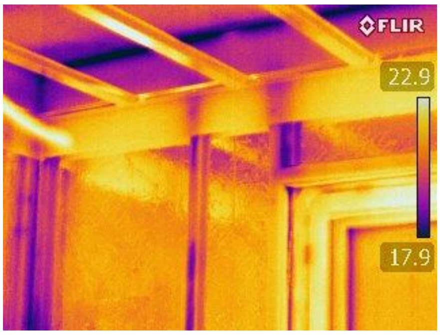
Thermogram 1 illustrates the overshadowing effect of the high reflective coating of the insulation



1st floor apartment – Internal view of external wall, West Façade. Ceiling to wall junction and window detail. (Bedroom)

Digital Image 2 Junction detail

Thermogram 2 Junction detail



However, since the iCT_Th test was to be repeated once the insulation was covered as part of the construction process, and one of the aims of the test was to understand the difficulties which can be encountered for both the researchers, developer and building contractor the test proceeded. Despite the circumstances with the insulation material the findings are being documented as learning as one of the outputs of the HGH project so that other developers, timber frame manufacturers and researchers can learn from the process. The process undertaken to analyse the thermograms involved thermally tuning each image prior to interpreting the results. For internal surveys, any colours indicating extremities of cold entering the building are potential issues (dark blues, purples and black) [28]. But, it is acknowledged that the accuracy of the tuning of the thermograsms relies on the environmental conditions being recorded accurately and with calibrated equipment; the camera was in focus; and the reflective and atmospheric temperatures are recorded for each surface under investigation by the thermal camera. Temperature bars to the right hand side of each thermogram provide a reference to the scale used. (For ease of comparison, all internal images have been given the same temperature range 10°C - 22°C and the external images a range of 1.5°C-3.5°C)" [28].

5 Discussion

The development of the test has shown important results to the thermography practitioners. Some of the main learning outcomes from the case study outlined in this paper are described here. It is imperative for the test to be arranged with significantly more time in advance than it might be expected; this is due to the fact that there are many variables affecting the successful undertaking of the test. Allowing time for setting up of the equipment (fan heaters, extensions, and temperature and humidity probes) and site checking (feasibility of test, reachability and safety of the specimen, electric power availability, and minimal interfering with site operation). Weather conditions must be monitored to avoid rain phaenomena (increasing the heat flow exchange internal to external) and direct sun exposition (overcast sky is the ideal condition). Previous assessment of the surface materials of walls should be thoroughly undertaken, if high reflective materials are exposed, it will be better to undertake the thermography test after the material is suitably covered, i.e. after plasterboard is installed. Concluding, the researchers have learnt that the variables entering the thermography test are high and difficult to control for the success of the survey. It is extremely difficult to prevent the unexpected, however good management and a protocol to follow is very useful. The protocol must contain information about the issues that can be encountered, addressing them and suggesting ways to solve the most likely problems to be encountered. Continuing to validate these methods will be of extreme value to this field of research. The HGH research team is aiming to repeat the test in May 2019 once the plasterboard has covered the reflective insulation. However, with rising daily temperatures and solar radiation, the researchers may have to wait until the autumn and conduct another iCT test such as the smart fire performance test, which is not weather dependent.

6 Conclusion

This paper has given context to the HGH project, the BPA protocol and challenges and benefits of implementing thermography tests on live construction sites. Performance problems (particularly fire safety) are more important considerations in timber buildings, which is a design, construction and manufacture challenge. This study is adding further evidence of the suitability and advantages of implementing in-construction testing in the development of efficient and more sustainable buildings, by analysing the challenges of implementing these practices in real live projects. This is a step forward towards the evaluation of the overall benefits of undertaking these tests, in terms of achieving greater energy efficiency of buildings, increasing thermal comfort and occupants' safety and well-being. This can be achieved by tackling important issues such as the Safety Gap and the Performance Gap and finding viable solutions.

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