Energy and Buildings 76 (2014) 130–142

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Combining thermography and computer simulation to identify and assess insulation defects in the construction of building façades

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ARTICLE INFO

Article history:
Received 16 November 2013
Received in revised form 23 February 2014
Accepted 26 February 2014
Available online 12 March 2014

Keywords:
Infrared thermography
Thermal bridging analysis
Modelling and simulation of heat transfer
Non-destructive testing (NDT)
Construction quality
Low carbon buildings
Building façade
Building fabric performance
Energy efficiency
Thermal performance

ABSTRACT

Thermography is a non-destructive testing technique used to evaluate the thermal performance of buildings, typically post-construction. However, establishing objective criteria for the interpretation of test results is not straightforward and the process can appear subjective. In building design, computer modelling may be used to analyse the thermal performance of construction details, including the expected distribution of surface temperatures at junctions and openings. The objective of this paper is to explore how the two techniques may be used together to support the identification and assessment of insulation defects in the construction of building façades. Firstly, a literature review identifies the main parameters relevant to modelling heat transfer through construction details and also the parameters that influence the assessment of surface temperatures by thermography. Combining the two techniques can support thermal image interpretation and the assessment of defect severity. Procedures to ensure a consistent approach between the two techniques are developed. Two case studies demonstrate the application of these procedures and illustrate the complementary use of modelling and thermography in a practical context. The approach discussed in the paper could help to verify the as-built energy performance of new buildings by linking design predictions of thermal performance with thermographic testing.

1. Introduction

Thermography is a non-destructive test method used in a variety of building applications, including: assessment of the continuity of insulation and façade energy efficiency [1–3]; identifying locations of air leakage [4,5]; monitoring internal air temperatures (with a low-cost measuring screen system) [6]; the inspection of electrical and mechanical building services [7,8]; detecting and mapping moisture within building structures [9]; and identifying delamination of external wall finishes [1,10,11]. A review of many of these applications is provided in Balaras and Argiriou [12]. The technique involves using an infrared (IR) camera to assess variations in surface temperature over building elements, such as external walls. Discontinuities in the insulation layer or moisture penetration result in localised changes to the thermal properties of building structures which under suitable conditions, can be identified using thermography. A qualitative method for the detection of thermal irregularities in building façades is specified in BS EN 13187 [13].

Heat transfer modelling involves the use of numerical methods to predict the thermal response of a physical system to specified environmental conditions. A typical application in building design is the evaluation of thermal bridging at junctions and around openings in the building envelope [14,15]. In this case, modelling may be used to predict minimum surface temperatures for the purpose of assessing the risk of condensation and mould growth. Heat flows can also be quantified using numerical methods so that performance parameters, such as the linear thermal transmittance (ψ-value) of a thermal bridge, can be determined. Conventions for defining model parameters and procedures for the validation of computer software have been established in ISO 10211 for these applications [16]. Linear thermal transmittance is defined in ISO 10211 as the “heat flow rate in the steady state divided by length and by the temperature difference between the environments on either side of a thermal bridge” [16]. It is a measure of the additional heat loss that can occur in building façades as a result of changes in geometry or material properties (i.e. variation in thermal conductivity). ISO 10211 specifies how numerical methods should represent the geometry of the part of the façade under

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http://dx.doi.org/10.1016/j.enbuild.2014.02.080
0378-7788/

consideration, the thermal boundary conditions for the model and calculation rules.

This paper considers how thermography and heat transfer modelling can be used together to assess the thermal performance of building façades and, moreover, how this can provide a more comprehensive analysis than is possible through the use of one technique in isolation. The scope for two complementary uses of these techniques is considered:

1. Heat transfer modelling can be used to calculate an expected surface temperature distribution over a building element. The modelling results can be compared with thermal images obtained from an in situ survey to improve diagnostic capability.
2. If a defect is identified by a thermographic survey, heat transfer modelling may be used to assess its severity in terms of additional heat loss.

In particular, it is proposed that through combining these two techniques it is possible to verify that the as-built thermal performance of new buildings is consistent with that predicted at the design stage.

Thermography and heat transfer modelling have been used together in other research studies and the relevant literature is reviewed in the next section of the paper. However, these studies do not provide a detailed account of the factors that should be considered when combining the two techniques. To address this gap in existing knowledge, procedures for combining thermography and heat transfer modelling in a consistent way are developed in the paper. The practical utility of using the two techniques together is also illustrated through two case studies. Given this practical emphasis, the paper aims to be relevant to both researchers and professional thermographers.

2. Background

2.1. Energy efficient buildings

The motivation for investigating the complementary use of thermography and heat transfer modelling is the increasing emphasis placed on enhancing the energy efficiency of buildings. In the European Union, the Energy Performance of Buildings Directive adopted in 2012 established a legal requirement for new buildings in all member states to be "nearly zero energy" by 2020 [17]. Similarly, upgrading the energy efficiency of the existing building stock is recognised as a priority if the European 20-20-20 targets [18] and longer-term targets for climate change mitigation are to be achieved.

In the domestic sector, recent research in the UK has provided evidence that the thermal performance of new dwellings can be significantly below design predictions [19]. As a strategy towards addressing this "performance gap", previous work by the authors has investigated the scope for conducting thermographic inspections during the construction process to support the management of construction quality on site [20,21]. A complementary study has also used thermography to investigate the quality of installation of retrofitted external wall insulation (EWI) in existing dwellings [22]. Here, thermography found evidence of thermal bridging following completion of the EWI installations, emphasising the importance of achieving continuity of insulation at junctions and also helping to identify quality control issues. In both cases, thermography has been used to assess the effectiveness of energy efficiency measures. The complementary use of heat transfer modelling represents a possible means of extending the scope of these assessments. Other research studies that have combined the use of thermography and heat transfer modelling are reviewed below.

2.2. Previous research

A range of research studies have utilised a combination of thermography and numerical modelling techniques to evaluate the thermal environment. Türler et al. [23] developed laboratory procedures "designed to minimise error in infra-red temperature measurements for research efforts that quantify surface temperatures in order to compare them to computer simulated data". This research was undertaken to validate a complex heat transfer model under laboratory conditions. Even in a carefully controlled laboratory environment the accuracy of temperature measurement with a high resolution IR camera was $\pm 0.5\,^{\circ}$C. Typical measurement accuracy in the field (i.e. in real buildings) might be expected to be in the region of ± 1–$2\,^{\circ}$C [23].

Asdrubali et al. [24] investigated the use of thermography to quantify the impact of thermal bridges. Both laboratory tests and numerical simulation were employed to validate a methodology for the simple in situ assessment of thermal bridging using thermography. This methodology can be used to calculate the additional heat loss from a thermal bridge, but does not consider other impacts such as the risk of surface condensation and mould growth. Zalewski et al. [25] used thermography to characterise the thermal performance of steel-frame pre-fabricated walls with the results compared to steady-state numerical simulations. A preliminary study reported in Fox et al. [26] also compared thermography and numerical simulation for investigating the transient behaviour of materials. However, the compatibility of thermography and simulation data is not discussed in detail in any of these publications.

Wróbel and Kisilewicz [27] investigated the practical use of thermography for the in situ assessment of thermal bridges. They identified the application of numerical simulation for predicting surface temperatures at openings and junctions for comparison with thermal images. Furthermore, they consider the benefits of using numerical simulation with thermography for quantifying the impact of thermal bridges in terms of energy performance and risk of surface condensation. However, the parameters that influence the comparability of numerical simulation and thermography are not discussed in detail. A more detailed analysis focussed on the influence of different climatic parameters on thermography is provided in Lehmann et al. [28]. This study found that solar- and IR-radiation could result in significant perturbations to the external surface temperatures of buildings which could therefore interfere with accurate interpretation of thermal images. However, these perturbations decay relatively rapidly after sunset in lightweight construction types or following 1–2 days of overcast skies for heavyweight construction types. A sensitivity analysis was used to determine the influence of other climatic parameters (e.g. wind speed) and develop criteria for conducting reliable thermographic inspections. In the context of refurbishment projects, Cox-Smith [29] used numerical simulation to investigate the effect of gaps in the insulation of timber-frame construction and predict the expected surface temperature distribution associated with this type of defect.

The literature reviewed above identifies that numerical modelling is a technique used to facilitate the analysis and interpretation of thermal images. However, there is limited critical evaluation of the difference between predicting surface temperatures by modelling and measurement in situ using thermography, with the exception of Lehmann et al. [28] who developed a simulation model for a particular external wall configuration that was validated against detailed meteorological observations. Nonetheless, there remains a lack of practical guidance for those wishing to combine the two approaches. This gap in existing knowledge is addressed in later sections of this paper.