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

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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.

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

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 & 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" (ibid.). 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 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 minimize 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 ± 0.5°C. Typical measurement accuracy in the field (i.e. in real buildings) might be expected to be in the region of ± 1–2°C (ibid.).

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 & 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.

3 Thermal bridging analysis

3.1 Modelling parameters

Heat transfer through plane structures is one-dimensional whereas thermal bridges are characterised by two- or three-dimensional (2D or 3D) heat flow. A summary of the main modelling parameters used for the assessment of thermal bridges by numerical methods is provided in Table 1. ISO 10211 states that in many cases “numerical calculations based on a two-dimensional representation of the heat flows provide results of adequate accuracy, especially when the constructional element is uniform in one direction” [16]. However, Ward & Sanders identify that some construction details, such as heat transfer at the corner of a ground floor, should be modelled in three-dimensions [15]. Another consideration, relevant for the comparison of modelling with thermography, is that a 2D projection of surface temperatures can be calculated using a 3D model. This type of projection (i.e. a map of surface temperatures) enables a more direct comparison with the surface temperature distribution recorded in a thermal image.

3.2 Evaluation of thermal bridges

Two performance parameters are typically calculated for the assessment of linear thermal bridges:

1. Temperature factor (f_{Rsi}); and
2. Linear thermal transmittance (ψ-value).

The temperature factor is calculated as follows [14]:

$$f_{Rsi} = (T_{si} - T_e) / (T_i - T_e) \quad \text{Equation 1}$$

where T_{si} = *internal surface temperature;* T_e = *external temperature; and* T_i = *internal temperature*.

To avoid surface condensation and the risk of mould growth, the temperature factor should be above a critical value. Different values of the critical surface temperature factor may be applied for different building types [14]. In dwellings, the recommended value of the 'critical surface temperature factor' (f_{CRsi}) is 0.75 (ibid.)[14]. This relationship is expressed as follows:

$$f_{Rsi} \geq f_{CRsi} \text{ (= 0.75 for dwellings)} \quad \text{Equation 2}$$

The linear thermal transmittance is calculated based on the difference between heat transfer through the bridged structure and that through the plane structural elements. It therefore represents the extra heat flow through the thermal bridge. More formally, the linear thermal transmittance is calculated as follows:

$$\psi = L_{2D} - \Sigma U.l \quad \text{Equation 3}$$

Where L_{2D} = *the thermal coupling coefficient calculated using a 2D numerical model;* $\Sigma U.l$ = *the sum of the thermal transmittance of each 1D building component separating the two environments being considered multiplied by the length over which it applies.*

This calculation is illustrated for the corner of an external wall in Figure 1.

3.3 Simulation software

Tilmans & Van Orshoven [34] provide an overview of the current computer software available for the assessment of thermal bridges. The features that differentiate these software packages are briefly summarised below:

- Modelling capabilities: some software is only able to analyse heat transfer problems, whereas others are capable of modelling heat, air and moisture movement or can be used to model a wider range of physical phenomena.
- 2D or 3D model geometries. Some software is also limited to rectangular models, whereas others can calculate free-form models.
- Steady-state or transient simulations.
- Free/open-source/commercial software.

A comparison table is provided in Tilmans & Van Orshoven (ibid.) summarising the functionality of different thermal bridging analysis software against these criteria. Selection of an appropriate software package will be informed by the characteristics of the problem under investigation. As previously discussed, certain heat transfer problems require analysis using 3D geometrical models.

4 Reading surface temperatures with thermography

4.1 Calibration of thermal images

The representation of surface temperatures using thermography involves a calibration process. An IR camera does not measure temperature directly. The detector of an IR camera is sensitive to radiative flux within a certain spectrum of infra-red wavelengths. The detector signal is then processed according to algorithms in the IR camera so that the measured radiative flux is converted into a temperature reading. The main parameters involved in this calibration process are summarised in Table 2. These parameters are measured during a thermographic inspection as discussed in Section 4.3 (note that typical values of emissivity may be found in material data charts e.g. in Appendix A of Clarke [35]).

4.2 Measurement of infra-red radiation

There are three sources of IR radiation received by the camera detector: emission from the object; emission from the atmosphere; and reflected radiation from the surroundings. This is illustrated in Figure 2. Note that the radiation emitted and reflected from the object is attenuated through atmospheric transmission. It is also assumed in Figure 2 that the object is “opaque” (i.e. there is zero transmission of IR radiation through the object).

The total radiant energy emitted by an object is related to its emissivity according to Stefan-Boltzmanns Law, which states that [36]:

$R = \varepsilon \sigma T^4$ *Equation 4*

Where R = *irradiance* (Wm^{-2}); ε = *emissivity;* σ = *Stefan-Boltzmann constant* ($5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$); T = *Temperature (Kelvin)*

In general, the emissivity of an object varies with its temperature, the wavelength of radiation and the angle at which it is viewed with an IR camera. For solid materials the variation of emissivity with temperature and wavelength can usually be ignored within the range of temperatures typically encountered within buildings (ibid.). Furthermore, the variation of emissivity with angle of view does not vary significantly for angles up to 45° from perpendicular [2]. For the purposes of thermal image calibration, an object is typically assigned a single value of emissivity. Objects with high emissivity emit a relatively higher proportion of IR radiation and reflect a correspondingly lower proportion of IR radiation from the surroundings. This makes them more reliable for assessing surface temperatures using thermography in comparison to objects with low emissivity. Another issue with low emissivity surfaces are that they reflect more radiation from high temperature objects such as light bulbs (and even from people). This may need to be accounted for when evaluating a thermal image. In particular, glass surfaces behave like a specular (or mirror-like) reflector of IR radiation and it is therefore difficult to take temperature measurements from them using thermography.

The total radiation reflected by the object is related to the temperature and emissivity of the surroundings and the object reflectivity. For opaque bodies, the reflectivity (ρ) is calculated as follows:

$\rho = 1 - \varepsilon$ *Equation 5*

For thermal image calibration, the surrounding environment is treated as a uniform blackbody and is assigned an “effective” temperature. This is sometimes referred to as the reflected apparent temperature (RAT) or ambient temperature (T_{amb}). Atmospheric emission and transmission varies with air temperature and humidity and the distance from the object [37].

4.3 Recording of environmental data

For thermal image calibration, the internal and external air temperature and relative humidity should be recorded during a building thermographic survey (and also the wind speed and direction for reference to assist with the interpretation of survey results). The reflected temperature of the surroundings can be calculated using the IR camera by measuring the average temperature of the surrounding surfaces that exchange infra-red radiation with the target object (i.e. pointing the IR camera at the sources of reflections). The temperature readings should not be compensated for reflections or atmospheric attenuation and the measurements should be averaged in proportion to their view factor with the target object. Alternatively, a highly reflective and diffusive aluminium mirror can be placed on the target object and readings taken from it to calculate the reflected temperature [38]. A sheet of aluminium foil that is crumpled and then re-flattened is sometimes used [24,39]. Values of each parameter in Table 2 are then entered into the IR camera or image analysis software to calibrate the thermal image.

5 Combining thermography and computer simulation

5.1 Practical applications

Having calibrated a thermal image obtained through a thermographic survey, modelling supports two types of analysis discussed below.

(i) Expected temperature distribution

The use of modelling to generate an expected surface temperature distribution is effectively a substitute for a “reference thermogram”. According to BS EN 13187 “reference thermograms may either be produced in a laboratory or obtained from field tests made on actual buildings” and aim to represent the conditions anticipated during a thermographic inspection [13]. Thus, reference thermograms are based on physical models of the structure under examination whereas numerical methods can be used to produce a virtual model. The potential benefit of virtual models over laboratory or field -based measurements are that a range of construction details can be simulated and analysed relatively rapidly. The construction of an equivalent range of physical models would be considerably more labour and resource intensive. A reference thermogram provides a basis for the qualitative comparison of the expected surface temperature distribution with that measured during a thermographic survey. This supports the interpretation of thermal images and the diagnosis of defects present within the structure.

(ii) Calculation of heat flows

The effect of thermal bridging on the energy efficiency of the building fabric can be calculated at the design stage using modelling (e.g. determination of ψ-values). If a defect is identified by a thermographic survey then the effect of this defect on energy performance may also be estimated through modelling. This assumes that the cause of the defect has been properly established, which may require additional investigation (e.g. a borescope survey) or reference to design drawings or photographs of the construction process (if available). By calculating the impact of the defect, such as an increased ψ-value at a junction, it may be possible to quantify the cost to the building owner in terms of the resulting reduction in operational energy performance. This type of analysis could inform the decision to proceed with remedial measures or justify a claim for financial compensation.

These two applications apply to different stages in the process of thermographic examination as illustrated in Figure 3. This is a modified version of the stages of thermographic examination defined in BS EN 13187 [13] (modifications are highlighted in the diagram). A case study that illustrates the first application introduced above – the use of modelling to generate reference thermograms – is discussed in the next section of the paper.

5.2 Case Study 1: perimeter insulation for an intermediate timber floor junction

Case study description

An overview of workmanship issues that are a typically a concern for compliance with energy efficiency requirements in UK Building Regulations is reported in [40]. A summary is provided in Table 3. One example is the omission of insulation from the perimeter of an intermediate timber floor junction. This type of defect was documented in a research project carried out by Leeds Metropolitan University which surveyed a number of construction sites in England during 2004 [41]. The researchers in this study found no evidence for the placement of perimeter insulation at any of the sites visited. Here, modelling is used to investigate the expected surface temperature distribution resulting from missing perimeter insulation for an intermediate timber floor junction.

HEAT3 modelling

Two models were constructed using the HEAT3 software:

- An intermediate timber floor junction with perimeter insulation in place (Model 1.a); and
- A second model without perimeter insulation (Model 1.b)

A section through the junction is shown in Figure 4. A simplified representation of the actual 3D model geometry defined in HEAT3 for Model 1.a and 1.b is shown in Figure 5. The boundaries of the model geometry are consistent with modelling rules specified in ISO 10211 (a minimum of 1m from the wall-floor junction). The floor joists are at right angles to the external wall and supported in line with the wall studs (at a spacing of 0.6m). The thermal properties of materials and boundary conditions are also defined in Figure 4. Note that the thermal resistance of all air spaces in the model have been calculated in accordance with Annex B of ISO 6946:2007 [32]. For example, in Model 1.b the 80mm perimeter insulation of mineral wool (with conductivity 0.037 W/m·K) is replaced by an air void with an equivalent thermal conductivity of 0.42 W/m·K. Also, the floor void is partitioned into separate air spaces with different thermal resistances in both models following the procedure defined in Ward & Sanders [15]. For all other components in the model, typical values for thermal conductivity as given in Anderson [30] have been used.

The calculated temperature profiles for a section through the intermediate floor junction under steady-state conditions are shown in Figure 6. There is a marked difference between the temperature gradient across the perimeter insulation in Model 1.a and the void missing insulation in Model 1.b with a corresponding influence on the temperatures at the internal surfaces. This is more readily visualised by a 3D projection as given in Figure 7. The lower surface temperatures along the top of the wall and also at the ceiling level adjacent to the junction are caused by the missing perimeter insulation. A qualitative comparison of the two models suggests that there is a distinctive thermal pattern associated with missing perimeter insulation in an intermediate timber floor junction and that this type of defect could therefore be detected by an internal thermographic survey (conducted under suitable conditions). However, this is not the case for the external surface and so an external thermographic survey would not be recommended for checking the installation of the perimeter insulation.

The temperature factor for Model 1.a is $f_{Rsi,1a}$ = 0.91 and for Model 1b is $f_{Rsi,1b}$ = 0.86. Neither junction would therefore be considered at risk of surface condensation and mould growth. For the junction with defects (Model 1.b), the temperature difference on the internal surface between the top of wall adjacent to the ceiling (i.e. in proximity to the defect) and an insulated part of the wall approaches 0.1°C (and 0.05°C where there are timber studs) for a difference between the internal and external boundary temperatures of 1°C. If a thermographic survey was conducted with an internal-external temperature difference of 10°C then these temperature differences would correspondingly increase by the same factor of 10. For example, assuming an internal temperature of 20°C and an external temperature of 10°C, the surface temperature at the top of the wall with missing perimeter insulation would be 18.6°C. Note the external temperature may need to be adjusted if the building is surveyed at night when there are clear skies as discussed later in the paper. This type of quantitative analysis, derived from the results of modelling, can assist with the interpretation of thermal images and diagnosis of defects within the construction. Furthermore, Case Study 1 shows how modelling can be used to generate images of the expected surface temperature distribution for building façades with and without defects. Comparison of these reference images (e.g. Figure 7) with *in situ* thermography test data could potentially help thermographers identify some common types of construction defect.

5.3 Comparing modelling results with *in situ* thermography test data

For the effective comparison of heat transfer modelling with thermography there needs to be consistency between modelling approaches and the recording of thermal image data. This will involve following specific modelling conventions and also ensuring that thermograms are properly compensated for environmental conditions as discussed previously. Additional considerations are discussed below.

Assumption of steady-state heat transfer

For the assessment of thermal bridges, numerical calculations are often simplified by assuming steady-state heat transfer conditions (as in Case Study 1 above). Whilst it is possible to control the thermal conditions inside a building, diurnal variations in the external air and radiant temperatures mean that steady-state conditions are never fully realised. Mumovic et al. [42] show that the effects of transient conditions can be significant when assessing the risk of surface condensation and mould growth at thermal bridges (particularly for heavyweight construction). However, in relation to the use of numerical modelling with thermography, the effect of transient conditions is most important when it results in the inversion of boundary temperatures (i.e. when the principal direction of heat flow is reversed). In this case, the bridged part of the structure may have a different transient thermal response to the surrounding structure and consequently the surface temperature distribution may not correspond with that expected under steady-state conditions. For practical purposes, this means that thermal images obtained outside of the heating season in the UK, or under conditions where the building element has been exposed to direct solar radiation prior to the survey, may not correspond with the assumption of steady-state heat transfer. Otherwise, provided a relatively stable difference between internal and external boundary temperatures is maintained for a sufficient period of time, steady-state conditions are likely to be approached. This simplification is to a large extent supported by a parametric study of climatic parameters and their influence on thermography undertaken by Lehmann et al. [28]. There also needs to be a sufficient difference between internal and external temperatures in order to reliably identify defects in building façades using thermography. A larger internal-external temperature difference will enhance the thermal contrast between defective and nondefective areas. A minimum of 10°C is recommended as a “rule of thumb” for building insulation surveys [43].

Internal and external temperatures

The internal and external boundary temperatures for numerical calculations performed in accordance with ISO 10211 are defined in Table 1. To enable comparison with thermal image data, the environmental conditions measured during a survey should be used to define appropriate boundary temperatures in the model.

Internally, the “operative temperature” used in numerical calculations is equivalent to the “uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment” [44]. In general, the operative temperature is a function of the air temperature, mean radiant temperature and relative air velocity [45]. In ISO 10211 it is assumed that the operative temperature is equivalent to the arithmetic mean of the air temperature and mean radiant temperature. A globe thermometer can be used to measure the mean radiant temperature [46]. However, for well-insulated buildings under approximate steady-state heat transfer conditions the difference between the internal air temperature and mean radiant temperature is likely to be small (i.e. the air temperature and surface temperatures are similar). In this case, a simplifying assumption is that the internal boundary temperature for modelling purposes is comparable with the internal air temperature measured during a thermographic survey (except where there is significant radiant asymmetry).

Externally, ISO 10211 defines the external boundary temperature as being equivalent to the external air temperature, assuming that the air temperature and radiant temperature seen by the surface are equal. However, the mean radiant temperature of the sky varies significantly between night and day and with the extent of cloud cover. A useful concept to introduce here is the sol-air temperature, calculated as follows:

$$T_{sol\text{-}air} = T_e + (\alpha \,.\, I_{sol} - \Phi)R_{se} \qquad \textit{Equation 6}$$

Where $T_{sol\text{-}air}$ = *sol-air temperature;* T_e = *external air temperature;* α = *absorptance of surface;* I_{sol} = *global solar irradiance;* Φ = *thermal radiation to the sky;* R_{se} = *external surface resistance*

Therefore, the sol-air temperature includes the effect of solar heat gain on building surfaces and thermal radiation with the sky. It is equivalent to the “driving force of heat flow” through the building element [46].

For the purpose of comparing the results of modelling with thermal image data, it is useful to consider two peaks in the sol-air temperature that occur during a daily cycle when there are clear skies. The first occurs during the middle of the day when solar irradiance is at its maximum. In this case, the sol-air temperature may significantly exceed the external air temperature (e.g. on south-facing orientations of a building in the UK). Note that it is not usually recommended to conduct a thermographic survey under these conditions [2]. The second peak occurs at night when there are no solar heat gains (i.e. $I_{sol} = 0$ in Equation 6). Thus, during the night the sol-air temperature may be significantly below that of the external air temperature. To account for this, it is recommended that an adjustment is made to the external boundary temperature used for modelling purposes when comparing the results with a thermographic survey conducted during the night. A procedure for estimating the sol-air temperature under these conditions is discussed below.

Szokolay states that the radiant emission term in the sol-air temperature calculation usually takes a value between $\Phi = 90$ W/m^2 for a clear sky and $\Phi = 20$ W/m^2 for a cloudy sky for horizontal surfaces [46]. According to ISO 13790, a dimensionless view factor, $F_r = 0.5$, is applied to these values for an unshaded vertical surface [47]. The normal design value for external surface resistance given in ISO 6946 is $R_{se} = 0.04$ m^2·K/W [32]. Using this data, it is possible to calculate the difference between the sol-air temperature and external air temperature: a parameter referred to as the "sol-air excess temperature" (δT_e) [46]. Values of the sol-air excess temperature are given in Table 4. It is recommended that these values are applied as an adjustment factor to the external air temperature used for modelling purposes (for subsequent comparison with thermographic surveys of unshaded surfaces conducted at night, particularly when there are clear skies).

The measurement or calculation of the sol-air temperature during daylight hours would enable an equivalent adjustment factor to be derived for external air temperatures (i.e. for daytime thermographic surveys of the interior of a building). However, tabulating these adjustment factors would be considerably more complex, since during the day the sol-air temperature varies according to the position of the sun (i.e. time of day), orientation of the building surface and extent of cloud cover. Therefore, in the absence of specific site data, a simplifying assumption is to use external boundary temperatures as defined in ISO 10211 for modelling purposes (i.e. the external air temperature for daytime surveys).

Variations in surface resistance

In steady-state heat transfer calculations, the combined effects of convective and radiative heat transfer which occur at building surfaces are usually simplified into a single expression: the surface resistance. Standard design values of surface resistance for the internal and external boundary conditions are stated in ISO 6946 [32]. CIBSE Guide C describes more detailed approaches to calculating the separate coefficients of convective and radiative heat transfer at internal and external surfaces [48]. However, the underlying physical processes can be complex and the discussion here is limited to the basic principles relevant to the comparison of heat transfer modelling with thermography.

In terms of standard design values, internal surface resistances are higher than external surface resistances for all corresponding directions of heat flow. This is because in calculating these values it is assumed that a “still air” condition is satisfied internally whereas a wind speed of 4m/s is assumed externally and hence the convective component of heat transfer is greater [48].

If air movement is not significant (i.e. the still air condition is satisfied), and surface temperatures are similar and do not significantly deviate from the air temperature, then a simplifying assumption is to use the standard design values for internal surface resistances for modelling purposes. In the absence of more detailed measurements or calculations this provides a consistent approach likely to be representative of the conditions encountered during a thermographic survey.

External surface resistances can be adjusted according to the wind speed using the calculation procedures defined in CIBSE Guide C. However, there will be variation in wind speed over different aspects of the building envelope depending on the wind direction. Therefore, a simplifying assumption is again to use standard design values for the external surface resistances for modelling purposes, unless more accurate measurements or calculations can be made.

One complication to these modelling assumptions concerns junctions between building elements. For a heated building inspected from the inside, the junction of two plane surfaces typically appears colder than the adjacent surfaces when viewed with an IR camera. An example is shown in Figure 8.

This phenomenon is sometimes referred to as a “corner-effect” [43]. Three factors may contribute to the corner-effect for an internal survey:

1. The two-dimensional heat flow that occurs at the external corners of a building is a thermal bridge, and hence lower surface temperatures might be expected in the corner in comparison to the surrounding structure.

2. Air movement in the corner is reduced because of the change in geometry. This alters the local convective heat transfer coefficient. For example, ISO 13788 recommends that an internal surface resistance of 0.25 $m^2 \cdot K/W$ is used for modelling purposes to take into account the “worst case” effect of corners [49]. This is a higher surface resistance compared to the standard design values used in heat flow calculations according to ISO 10211. Also, space heaters may not distribute heat as effectively in the corners of the room.
3. The characteristics of radiant heat exchange are different in a corner in comparison to a plane area of wall far from a corner. In simple geometrical terms, the corner “sees itself” with the effect that a larger proportion of radiant energy exchange occurs between the proximate surfaces in the vicinity of the corner. Since it has been established above that surface temperatures in the corner are expected to be lower than those of plane surfaces far from a corner, this is equivalent to saying that there will be a smaller reflected component of IR radiation at a corner that would be received by an IR camera during an inspection.

The cumulative effect of these factors results in corners appearing colder in a thermal image. This means that corners are more likely to be considered at risk of surface condensation if applying the critical temperature factor for surface condensation stated in Ward [14]. However, the critical temperature factor of 0.75 for dwellings is intended to apply to the results of numerical calculations (ibid.). Following standard conventions, numerical calculations do not take into account factors (2) and (3) stated above, and therefore applying the same critical temperature factor to a thermal image is likely to result in more conservative results. To account for this, one possible approach is to evaluate the minimum internal surface temperature in a thermal image from a short distance from the corner. This suggested approach is similar to that recommended for modelling a three dimensional corner at a ground floor in Ward & Sanders [15], where the temperature factor is assessed 10mm from the coldest point in numerical calculations.

Dimensional tolerances

The final parameter considered for the comparison of numerical calculations and thermography is related to the definition of model geometry. For the purpose of calculating the design thermal performance of a construction detail it is typical to assume good workmanship. This assumption is reinforced by having to define continuous material boundaries for the model geometry within numerical calculations. However, acceptable tolerances within site construction do not operate at the same absolute level of accuracy. For example, loose rolls of insulation laid over an uneven surface are unlikely to maintain perfect contact with the underlying structure. Therefore modelling may provide an optimistic estimate of thermal performance in cases such as this.

Having established above some procedures for comparing modelling results with *in situ* thermography test data, their application is illustrated with reference to a second case study.

5.4 Case study 2: Eaves junction

Case study description

The case study building comprises a row of terraced houses divided into 12 flats constructed in timber frame. A thermographic inspection of part of the building was completed during the construction phase. Following consultation with the site manager, the main bedroom in the flat at the most advanced stage of completion was selected for testing. A photograph of the bedroom and a plan layout is shown in Figure 9. The interior finish of the flat had progressed to the stage that the plasterboard had received a skim finish and a single coat of paint.

Thermographic survey: test procedure

On the morning of the test a 1.5kW electrical fan heater was installed in the bedroom (using a 110V supply for electrical safety reasons). Thermal images of the bedroom were recorded before switching on the heaters and again after a heating period of 4 hours. Measurements taken of the internal and external environmental conditions are summarised in Table 5. The use of the electrical heater resulted in a 9°C increase in the air temperature in the bedroom. The test set-up also satisfies the "rule of thumb" criteria of a difference of 10°C between internal and external temperatures recommended for identifying insulation defects using thermography [43].

Thermographic survey: results

Lower surface temperatures were observed at the junction between wall and ceiling in the test room, indicating higher levels of heat loss at the eaves. A quantitative analysis of this defect is given in Figure 10, which shows the variation of surface temperatures in the proximity of the junction (assessed along a line highlighted in the image).

The minimum temperature recorded in the region of the defect is 14.6°C. However, this measurement includes the corner at the junction between the wall and the ceiling. To account for the “corner effect” previously discussed, the minimum internal surface temperature for the insulation defect at the eaves is assessed a short distance from the corner. In this case, a value of T_{si} = 15°C is used giving a temperature factor f_{Rsi} = 0.7 (below the critical value f_{CRsi} = 0.75 for dwellings). Therefore, the defect at the eaves is considered at risk of surface condensation and mould growth (in the areas highlighted in Figure 11). Possible causes of lower surface temperatures at this location include: insulation not lapped over the top of the timber frame wall; insulation not rolled up to the eaves; and wind penetration over the brick outer leaf resulting in a thermal bypass over the top of the timber frame wall.

THERM modelling

To further investigate the issues observed at the junction between the wall and ceiling in the test room, the eaves detail with insulation installed correctly (i.e. lapped over the top of the timber frame wall and up to the eaves ventilator) was simulated using the THERM software. Figure 12 shows a section through the eaves detail and the corresponding temperature gradient across the junction. The calculated temperature factor is 0.89 for the as-designed detail. This confirms that the as-built detail is not performing as expected. Following the survey, the site manager was advised to check the installation of insulation at the eaves.

The calculated ψ-value for the eaves junction as-designed is ψ_{eaves} = 0.076 W/m·K. The default ψ -value for an “Accredited Construction Detail” at the eaves (with insulation at ceiling level) is 0.06 W/m·K [50]. This indicates that improvements could be made to the thermal performance of the eaves detail, for example by increasing the total thickness of insulation above the header stud at the top of the wall. In this case, modelling and thermography have been used together to identify thermal performance issues during construction and also to identify ways of enhancing the design of this particular detail. This type of feedback could help to improve the practices of design and construction teams in future projects.

6 Discussion

In summary, modelling parameters need to be defined in a way that is consistent with the environmental conditions encountered during a building thermography survey if there is to be an effective comparison of the results obtained by the two techniques. Some relevant procedures have been introduced in the previous section as general guidance to those wishing to undertake this type of analysis. The two case studies illustrate the practical applications of combining thermography and modelling. Other examples are discussed in a previous paper by the authors [51]

With reference to assessing the thermal performance of new buildings during and post-construction, the combination of thermography and modelling could help to enhance links between design and construction practices. In the UK context, it has been recognised that there exists a gap between the predicted and as-built energy performance of new buildings. Combining thermography and modelling provides an enhanced means of verifying the continuity of insulation of the building envelope. This type of fabric performance testing could complement current practice in building quality inspections (e.g. air leakage testing in the UK for regulatory compliance). Furthermore, modelling can be used to provide an objective basis for defining the expected results and hence reduce the apparent subjectivity of thermal image interpretation: a criticism that is sometimes made of thermography. However, currently both thermography and heat transfer modelling are, to some extent, specialist activities. Further research would be required to translate the potential of combining the two techniques into a workable scheme for verifying the thermal performance of new buildings.

In addition to assessing the continuity of insulation, thermography can identify other types of defect such as air leakage through the building envelope. A thermal anomaly resulting from air leakage has a different appearance than a defect resulting from missing insulation when viewed with an IR camera. Therefore, combining modelling and thermography does not alter the requirement for an informed interpretation of test results, even if it can support this process. This informed interpretation is particularly important when there are other environmental factors that influence the appearance of thermal images, such as the presence of heating equipment (i.e. radiant asymmetry) within a room. These factors may not be related to defects within the construction, but need to be considered when assessing test results. This is a limitation to thermography to the extent that the requirement for informed interpretation makes testing more complex, and probably also restricts the potential for the automation of testing procedures.

Similarly, modelling involves a large number of parameters with the corresponding risk of data input errors. Fortunately, the use of modelling in thermal bridging analysis is already well supported by literature e.g. [14–16] and by training programmes for those wishing to learn how to use specific software tools. Given the increasing emphasis on improving the energy efficiency of new and existing buildings, the use of modelling to analyse and enhance the thermal performance of building façades is likely to become more commonplace. Combining this type of analysis with thermography could help ensure higher performance is then delivered in practice.

7 Conclusions

Thermography and heat transfer modelling are complementary techniques for assessing the thermal performance of building façades during and post-construction. Combining the two techniques strengthens both the diagnostic and analytical stages in the process of thermographic examination. Modelling provides an objective basis for calculating the expected temperature distribution over a building surface for comparison with the results of a thermographic survey. It also enables the impact of an identified defect on the energy performance of the building to be calculated. However, there needs to be consistency between modelling assumptions and the environmental conditions that influence building thermography for this comparison to be reliable. The aim of the paper has been to identify the main parameters that should be considered when combining the two techniques and develop practical guidance for their complementary use.

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