Assessment of thermal bridging heat loss by means of the infrared thermography technique

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Abstract. Heat losses through thermal bridges substantially influence the thermal standard of a building envelope. At design stage, these losses, expressed in terms of the linear thermal transmittance or *Ψ*-value, can be estimated from tabulated values for standard building details or from numerical modelling. However, these approaches are not applicable for existing building envelopes with unknown internal structure. In these cases, in-situ measurement of the Ψ-value is necessary. In this study, a methodology to measure the actual thermal bridging performance is developed. The methodology is based on a quantitative infrared thermography technique, which is easy-to-use and implementable on any existing thermal bridge. To ensure high accuracy, temperature-dependent surface heat transfer coefficients are evaluated using the surface temperatures recorded by the infrared camera. The methodology has been validated under steady state conditions in a hot box device with excellent agreement.

Keywords: Building Envelope, Hot Box, Quantitative Thermography Technique, Thermal Bridging.

1 Introduction

Thermal bridging causes additional heat losses that can significantly degrade the building envelope thermal performance and therefore should be minimized. At the design stage, the *Ψ*-values that describe these heat losses are predicted by numerical simulations, according to the standard EN ISO 10211 [1]. For these simulations, construction details must be known which makes this approach not suitable for many existing structures. It these cases an in-situ measurement has to be used.

The one of the first researchers to use quantitative infrared thermography teqhnique (ITT) for measurement of the heat loss associated with thermal bridging was Benkő [2]. He defined an energy saving factor as the ratio of the heat losses through a building component with and without a thermal bridge. Likewise, Asdrubali et al. [3] described the heat loss related to thermal bridging as a ratio, the incidence factor I_{tb}, that shows the increase of heat loss in the presence of a thermal bridge. To obtain the U-value of a component influenced by thermal bridging U_{tb}, the I_{tb} obtained by means of the ITT can be multiplied by the U-value of building component not influenced by thermal bridge U_{1D}. Asdrubali et al. [3] measured this U_{1D} using heat flow meter (HFM) whereas Bianchi et al. [4] calculated it.

In many existing building envelopes, the calculation method is not feasible as the construction of the building envelope is not known. On the other hand, the HFM requires special skills to use and is time consuming.

The methodology presented in this paper allows quantifying the heat flow rate via a thermal bridge and the Ψ-value by means of the ITT solely, without using any tabulated values or other measurements methods. The current methodology accounts for variable convective and radiative heat transfer coefficients where a thermal bridge disturbs the temperature distribution. This approach is novel and in contrast with both Benkő [2] and Asdrubali et al. [3], who assumed the surface heat transfer coefficients h as constant at the thermal bridge and outside thermal bridge zone of influence. The methodology was tested in laboratory conditions and validated with hot-box measurements.

2 Methodology

As mentioned previously, measurement is the only approach available for assessing the heat loss caused by thermal bridging in an existing building envelope, where the construction details are not known. Up to now, no such a method has been standardized. This paper presents a methodology to evaluate the actual thermal bridge heat flow rate q_{TB} caused by the thermal bridge. The q_{TB} shows the additional heat loss through the building component due to the presence of the thermal bridge. The q_{TB} is obtained as a difference between the total heat flow rate q_{tot} and the uniform heat flow rate q_u that would occur if thermal bridge is substituted with a plain component.

The methodology is based on the surface energy balance, which equates the rate at which energy is transferred to/from the surface in conductive mode to the rate at which it is transferred from/to the surface in convective and radiative modes, under steady state conditions. It is important that the IR image includes the whole range of temperatures disturbed by thermal bridge together with the uniform temperature region typical of a part of the component outside the thermal bridge zone of influence. In Fig. 1, a sample IR image containing a thermal bridge is presented.

This methodology has been developed for indoor conditions with free convection. For methodology modified for the outdoor conditions please refer to [5]. The procedure is illustrated on an example of a vertical thermal bridge but it can be applied, with some alterations, to any linear thermal bridge. For the post processing, five sequential IR images of the same thermal bridge are used. On each of the IR image, an IR line is created (see Fig.1). In order to generate this line, three rows of pixels at the middle height of the IR image are chosen. Each pixel on the IR line indicates the average surface temperature of the centreline pixel and its eight adjoining pixels. Then, from the five IR lines, a mean IR line is created. The surface temperatures on this line are used for further calculations.

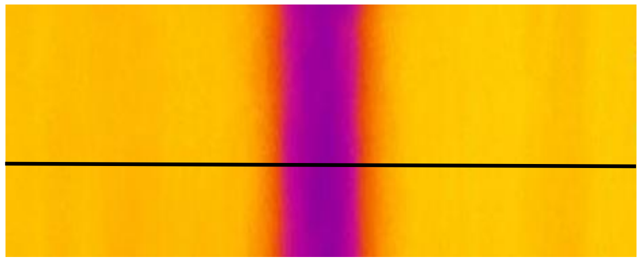

Fig. 1. Sample IR image of component with linear thermal bridge.

Firstly, the heat flow rate for each pixel (q_x) is found using (1). This equation is based on the assumption that the building indoor air temperature T_i is very similar to the surrounding temperature T_{sur}, which is very often the case. For other cases please refer to [6]:

$$q_x = l_x[(h_{cx}+h_{rx})(T_i - T_{sx})] \tag{1}$$

where:
q_x - heat flow rate for each pixel, W/m,
l_x - pixel length, m,
h_{cx} - convective heat transfer coefficient of a pixel, W/(m^{2}K),
h_{rx} - radiative heat transfer coefficient of a pixel, W/(m^{2}K),
T_i - indoor air temperature,
T_{sx} - surface temperature of a pixel, ^{o}C.

This methodology includes precise calculation of the convective heat transfer coefficient h_{cx} using (2) from the Nusselt number Nu_x, evaluated from the Churchill-Chu correlation [7]. The coefficients are evaluated for each pixel on the IR line as the pixels have variable surface temperatures:

$$h_{cx} = \frac{Nu_x\, k_x}{l_{ch}} \tag{2}$$

where:
l_{ch} - characteristic length in vertical direction over which h_{cx} applied, m,
k - thermal conductivity of air, W/(mK).

The radiative heat transfer coefficient h_{rx} is estimated for each pixel on the IR line using (3). This equation, similarly to (1), is used under the assumption that the building indoor air temperature T_i is very similar to the surrounding temperature T_{sur}:

$$h_{rx} = \varepsilon\sigma(T_{sx} + T_i)(T_{sx}^2 + T_i^2) \tag{3}$$

where:
ε - surface emissivity, measured during the thermographic survey (Section 5),
σ - Stefan-Boltzmann constant, W/(m^{2}K^4).

Using (4), the thermal bridge heat flow rate for each pixel, q_{xTB}, can be found:

$$q_{xTB} = q_x - q_{xu} \tag{4}$$

where:
q_{xu} - uniform heat flow rate for a pixel not influenced by thermal bridge, W/m.
By summing up the q_{xTB} for all pixels on the IR line, the thermal bridge heat flow rate q_{TB} can be found. Finally, the linear thermal transmittance Ψ-value can be determined using (5):

$$\Psi = \frac{q_{TB}}{(T_i - T_e)} \tag{5}$$

where T_e is the external air temperature, °C.
A more detailed description of this methodology can be found in [6].

3 Validation of the Methodology

The proposed methodology was validated under laboratory conditions in the hot box device, allowing controlling the ambient conditions. The experimental set up, showed in Fig. 2, enabled testing the same specimen first using the hot box method and then using the ITT, under a steady state. Both the hot box test and the thermography were carried out under the same conditions, summarised in Table 1.

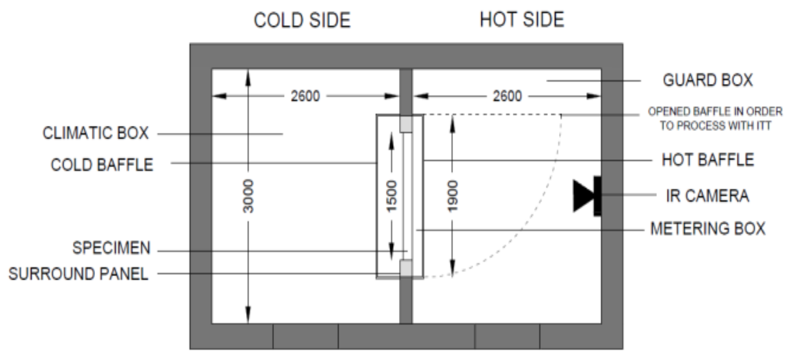

Fig. 2. Experimental set up (dimensions in mm).

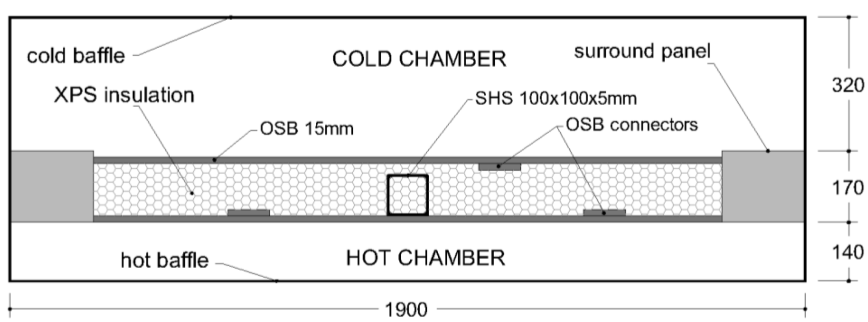

Fig. 3. Cross-section of tested specimen, inserted in hot box (dimensions in mm).

A specimen 1.5 m long and 1.5 m high purpose-built for the tests is shown in Fig. 3. It was made of structural insulated panels (SIP) consisting of low conductivity extruded polystyrene insulation (XPS) 125 mm thick with 15 mm thick oriented strandboard (OSB) facings on each side. A thermal bridge was created using a steel square hollow section (SHS) post 100 mm x 100 mm x 5 mm.

4 Hot Box Testing

The hot box testing was performed in accordance with EN ISO 8990 [8] at Cracow University of Technology, Department of Environmental Engineering. The hot box is built of a climate box, simulating the outdoor environmental conditions (cold side) and a metering box, simulating the indoor environmental conditions (hot side). To minimize the heat loss through the metering box walls, it is enclosed by a guarding box. The specimen was placed into a surround panel, which is made of low conductivity insulation to minimize any side heat losses. After the specimen was sealed into the surround panel, the metering box was attached on the hot side of the specimen. The hot air temperature designed for this test was +25°C. To ensure a uniform air temperature distribution in the metering box, a free convection with a wind velocity of 0.1 m/s was created. On the cold side of the specimen, in the climatic box, an isothermal baffle was attached. To simulate outdoor environmental conditions on this side, a wind velocity of approximately 1.50 m/s was induced and the air temperature was in the region of -5°C. The measurements were taken after a few hours of steady state conditions. The hot box was fitted with an AMR Ahlborn Wincontrol system that recorded data during the testing including the power provided to the hot box Φ_{in}, the air temperature, and the wind velocity on the cold side w_e and on the hot side w_i. Based on Φ_{in}, the surface heat flux $\dot{q}_{sp}$ was calculated. On the hot surface of the specimen, two thermocouples were attached in order to measure the surface temperature in the middle of thermal bridge T_{TB} and 0.40m away from the middle of the thermal bridge T_u.

Table 1. Hot box measurement at the steady state.

Parameter	Unit	Value
T_e	°C	-4.96
T_i	°C	24.82
w_i	m/s	0.1
w_e	m/s	1.55
Φ_{in}	W	22.70
$\dot{q}_{sp}$	W/m^2	7.01
T_{ni}	°C	24.50
T_{ne}	°C	-5.01

T_{ni} and T_{ne} are indoor and outdoor environmental temperatures that, according to EN ISO 8990 [8] and ISO 12567-1 [9], should be used for calculations based on temperatures measured in a hot box. Before the testing started, the hot box was calibrated to meet the requirements of EN ISO 8990 and EN ISO 12567-1. This was undertaken to account for any heat losses through the surround panel. In order to evaluate the q_{TB} and the Ψ-value, another identical specimen but without a thermal bridge was tested. Having the heat flow rate of this plain specimen, $\dot{Q}_{sp\,plain}$, which was equal to 14.65 W, the q_{TB} and Ψ can be obtained, using (6) and (7), respectively:

$$q_{TB} = \frac{(\dot{Q}_{sp} - \dot{Q}_{sp\,plain})}{H} \tag{6}$$

$$\Psi = \frac{q_{TB}}{(T_{ni} - T_{ne})} \tag{7}$$

5 Thermographic Testing

After the hot box testing was completed, the thermographic survey was carried out under the same wind and temperature conditions as the hot box measurements, summarised in Table 1. The survey began with measuring the reflected ambient temperature and the surface emissivity, as those two factors influence the accuracy of the IR camera reading. The reflected ambient temperature was measured using a direct method, in accordance to the ISO Standard 18434-1 [10] that was previously used by other researchers [3,11]. The surface emissivity was measured using the contact method, following the ISO Standard 18434-1. Afterward a series of IR images of the hot surface of the specimen was taken. To calculate the q_{TB} and Ψ-value in accordance with the methodology outlined above, a horizontal line (IR line) was created on each of five IR images. The mean IR line was derived from the five IR lines and used for calculations. The specimen was symmetrical, therefore only one half of the line was considered.

6 2D Heat Transfer Simulation

The hot box testing results were also used to validate a numerical 2D steady state heat transfer model, created using Ansys Fluent software. The specimen geometry as presented in Fig. 3 was analysed. A section of mesh in the central part of the specimen can be seen in Fig. 4.

Material thermal properties as well as the boundary conditions used in the simulations are given in Table 2. In this simulation, the standard boundary conditions, expressed as cold and hot surface heat transfer coefficients, were applied, in accordance with EN ISO 6946 [12].

The calculated temperature field in the part of the specimen impacted by the thermal bridge and of the plain element outside the thermal bridge zone of influence can be seen in Fig 5.

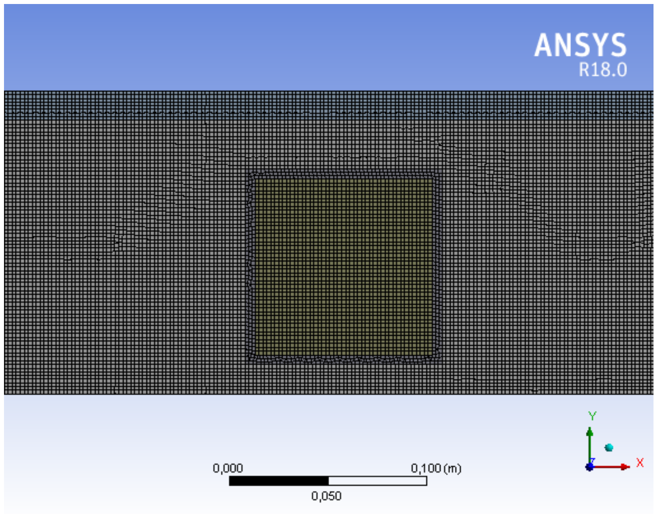

Fig. 4. A section of the meshed specimen.

Table 2. Material properties and boundary conditions.

Parameter	Unit	Value
XPS – thermal conductivity	W/(mK)	0.033
OSB – thermal conductivity	W/(mK)	0.13
SHS – thermal conductivity	W/(mK)	50.0
air temperature – cold side	^{o}C	-4.96
air temperature – warm side	^{o}C	24.82
surface heat transfer coefficient – cold side	W/(m^{2}K)	25.0
surface heat transfer coefficient – warm side	W/(m^{2}K)	7.7

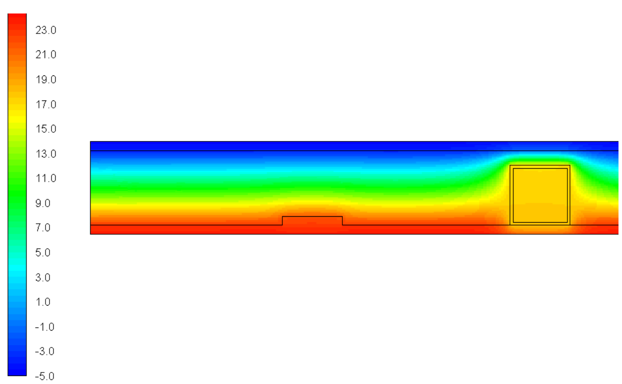

Fig. 5. Contours of temperature in part of the specimen.

7 Results

Fig. 6 illustrates the temperature distributions obtained by the ITT and from the 2D numerical model together with two temperatures (T_u and T_{TB}) measured by thermocouples during the hot box testing.

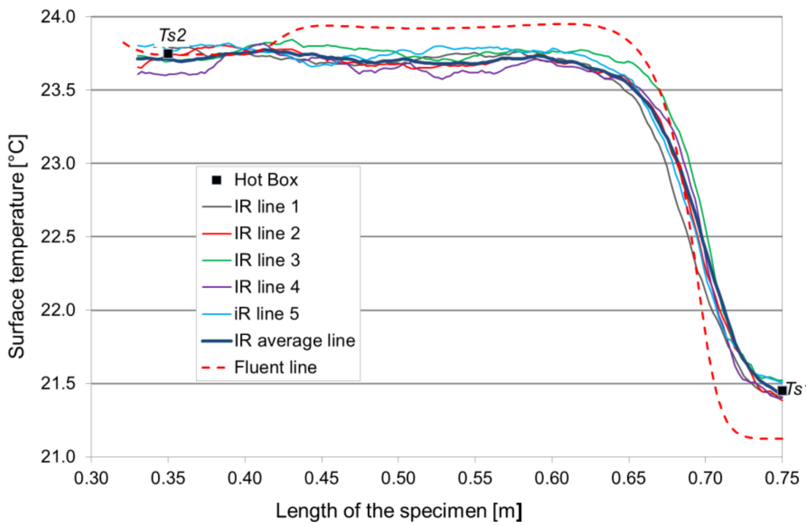

Fig. 6. Surface temperature derived from three methods.

The thermal bridge heat flow rate q_{TB} and Ψ-value obtained by means of the ITT and from the 2D model are compared to the hot box results in Table 3.

Table 3. Thermal bridge heat flow rate q_{TB} and linear thermal transmittance Ψ-value.

		hot box		*ITT*		*2D model*	*hot box/ ITT*	*hot box/ 2D model*
		results	*SD [%]*	*results*	*SD [%]*	*results*	*RD [%]*	*RD [%]*
q_{TB}	*W/m*	2.70	5.21	2.43	13.15	2.54	-10.00	-6.00
Ψ-value	*W/mK*	0.091	5.21	0.082	12.98	0.085	-9.89	-6.60

A relative deviation *RD* in the q_{TB} and the Ψ-value of -10% has been recorded between the ITT and the hot box results. However, the actual differences in the results are very small, 0.27 W/m for q_{TB} and 0.009 W/(mK) for the Ψ-value. It should be underlined that the high level of accuracy of the ITT results has been achieved due to precise evaluation of the convective and radiative heat transfer coefficients for each pixel on the IR line. In order to assess how exactly this approach influences the results, the q_{TB} and Ψ-value of the tested specimen was calculated using constant values of h_{cx} and h_{rx} related to the part of the specimen not influenced by the thermal bridge. The q_{TB} and Ψ-value evaluated using these constant values showed greater relative deviation of -18.5% while comparing to the hot box results that illustrates the correctness of the current approach of the precise calculation of h_{cx} and h_{rx}. The values q_{TB} and Ψ-value calculated with the 2D CFD model are also in a good agreement with the results measured in hot box. The relative deviations of q_{TB} and Ψ-values are equal to 6.0% and 6.6%, respectively.

8 Summary and Conclusions

A methodology for assessing the thermal bridge heat flow rate q_{TB} and the linear thermal transmittance Ψ-value by means of the indoor ITT has been presented. This methodology is based on the ITT solely. It is not necessary to use any tabulated values, for example thermal conductivities k or overall thermal transmittance U-values or other methods of measurements while applying the methodology to a thermal bridge located in a building envelope.

This methodology has been validated under laboratory conditions, in a hot box device with good agreement that provides a solid basis to apply it, with possible adjustments, to the real conditions. The current methodology can be practical during building energy efficiency assessment, especially where the building envelope structure is unknown.

The CFD simulations showed that it is possible to calculate the values indicating thermal bridge performance in an accurate way, but only if the specimen data (geometries and materials) are known thus is suitable at the building design stage.

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References

1. EN ISO 10211 Thermal bridges in building construction - heat flow and surface temperatures - detailed calculations (2007).
2. Benkő I.: Quantitative analysis of thermal bridges of structures through infrared thermograms. In Proceedings of International Conference on Quantitative Infrared Thermography Qirt 2002, Dubrovnik, Croatia, pp. 203–208. (2002)
3. Asdrubali F., Baldinelli G., Bianchi F.: A quantitative methodology to evaluate thermal bridges in buildings. Applied Energy, vol. 97, pp. 365-373. (2012).

4. Bianchi F., Pisello A., Baldinelli G., Asdrubali F.: Infrared Thermography Assessment of Thermal Bridges in Building Envelope: Experimental Validation in a Test Room Setup. Sustainability, vol. 6, pp. 7107–7120. (2014).
5. O'Grady M., Lechowska A.A., Harte A.M.: Quantification of heat losses through building envelope thermal bridges influenced by wind velocity using the outdoor infrared thermography technique, Applied Energy, (2017) http://dx.doi.org/10.1016/j.apenergy.2017.09.04
6. O'Grady M., Lechowska A.A., Harte A.M.: Infrared Thermography Technique as an in-situ method of assessing the heat loss through thermal bridging. Energy and Buildings, vol. 135, pp. 20–32. (2017).
7. Moran M. J., Shapiro H. N., Munson B. R., Dewitt D. P.: Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics and Heat Transfer. Hohn Wiley & Sons, Inc. (2003).
8. EN ISO 8990 Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated and guarded hot box. (1997).
9. EN ISO 12567-1 Thermal performance of windows and doors - Determination of thermal transmittance by the hot-box method - Part 1: Complete windows and doors. (2010).
10. ISO 18434-1 Condition monitoring and diagnostics of machines - Thermography Part 1: General procedure. (2008).
11. Fokaides P. A., Kalogirou S. A.: Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes. Applied Energy, vol. 88, pp. 4358–4365.(2011).
12. EN ISO 6946 Building components and building elements - Thermal resistance and thermal transmittance - Calculation method. (2007).