

Combining Infrared Thermography and Numerical Analysis for Evaluating Thermal Bridges In Buildings: A Case Study

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ABSTRACT

Energy dispersions for transmission in buildings with highly insulated envelope are mainly due to thermal bridges. And because the energy certification of buildings shall be based on real thermal performance and not on theoretical components, nowadays their incidence on energy saving is relevant. Currently, infrared thermography is considered exclusively as a qualitative tool to detect thermal irregularities in buildings, but thermographic inspection allows not only the localization of thermal bridges, but also the identification of temperature field and, therefore, the quantization of the energy losses through such elements of discontinuities. This approach marks a shift from a qualitative to a quantitative analysis of the thermographic image of a building. The aim of this paper is to study the effect of three different types of thermal bridge, estimated as a percentage increase of the homogeneous wall thermal transmittance. Results are obtained exclusively with thermographic surveys without further information on the wall stratigraphy. Finally, the methodology has been validated by comparing with the results obtained by numerical calculation.

Keywords– Heat losses, numerical simulation, quantitative infrared thermography, thermal bridges.

I. INTRODUCTION

Energy dispersions for transmission in buildings with well insulated envelope are concentrated in thermal bridges: it has been estimated that in buildings with average thermal transmittance between $0.15 \text{ W/m}^2\text{K}$ and $0.3 \text{ W/m}^2\text{K}$, a thermal bridge can affect the thermal energy needs from 28% up to 60% for Italian climatic zone E and D [1]. It is therefore necessary not only to correctly design structural node to minimize these singularities, but also to pinpoint accurate calculation methodologies to evaluate the benefits induced by a proper planning, and to ease the procedure of energy certification of buildings.

It is necessary to provide a simple and flexible instrument for the determination of the heat loss caused by thermal bridges, suitable to different types of buildings without any information about the structure or the wall stratigraphy.

In this paper, quantitative evaluation of thermal bridges through the use of active infrared thermography is performed, by the determination of the mean linear thermal transmittance, which computes the additional heat flow of linear thermal bridges.

From simple measurement of air temperature and through the analysis of the wall thermal images it is possible to estimate the effect of the thermal bridge as a percentage increase of the thermal transmittance of the wall characterized by one-dimensional heat flow (“undisturbed area”).

The effect of the thermal bridge is evaluated considering the increase of energy loss that it causes, and, therefore, the increase of thermal transmittance in respect to the wall “undisturbed”.

Three different thermal bridges in a real building have been analyzed and results have been validated in comparison with numerical simulations.

II. LITERATURE REVIEW

The classic methodology of calculation of thermal bridges (foreseen by standard UNI EN ISO 14683 [2]) are, in order of decreasing accuracy:

- numerical calculations (UNI EN ISO 10211 [3]) – expected accuracy $\pm 5\%$
- atlases of thermal bridges – expected accuracy $\pm 20\%$
- manual calculations – expected accuracy $\pm 20\%$
- reference values– expected accuracy $\pm 50\%$.

However, these methodologies have some limitations, like the need to know wall stratigraphy and construction details of thermal bridges, the long computation time and sometimes the complexity of modeling for numerical simulations, or the non-adherence to the real working conditions of materials. All these drawbacks suggested the use of a new experimental methodology for the evaluation of thermal bridges: the quantitative infrared thermography.

Currently, infrared thermography is considered exclusively as a qualitative tool to detect thermal irregularities in buildings’ envelopes (UNI EN 13187 [4]).

Nevertheless, quantitative infrared thermography has been studied in the last few years by several research groups and has been applied in different fields: Goldstein [5] introduced the use of quantitative infrared thermography for estimating the building envelope heat loss; H. Heinrich, K. Dahlem [6] have proposed thermography as a tool of investigation of near-zero-energy buildings; R. Albatici, A.M. Tonelli [7] have defined a methodology of calculation of thermal transmittance of a flat wall only by thermographic detection and the measurement of the indoor/outdoor air temperature (this method found also real application in a previous research of the Authors [8]); L. Zalewski, S. Lassue, D. Rousse, K. Boukhalfa [9] have studied the effect of steel joints in prefabricated building structures using thermal analysis and thermal flux; A. Wrobel, T. Kisilewicz [10] have found a thermographic quantization tool of thermal bridges by comparing the measured temperature values with those obtained by numerical simulation; I. Benko [11] proposed the quantization of thermal bridges by introducing a new factor defined on statistical basis; F. Asdrubali, G. Baldinelli, F. Bianchi [12] introduced a new factor which expresses the increase of thermal transmittance of the wall caused by the presence of thermal bridges; finally, T. Taylor, J. Counsell and S. Gill combined infrared thermography and computer simulation to identify and assess insulation defects in buildings' façades [13].

III. DEFINITION OF THERMAL BRIDGES

A thermal bridge is a zone characterized by thermal properties different from the rest of the envelope. Through a careful design of the components, it is possible to avoid the onset of "structural" thermal bridges determined by the local variation of thermal conductivity due to the heterogeneity of materials, but this is not possible for "geometrical thermal bridges", determined at junctions and around openings in the building envelope.

There are two main negative effects induced by thermal bridges: the reduction of the internal surface temperature, that may cause condensation and mold, and the increase of energy losses through the building envelope.

The contribution of thermal bridges to energy losses may be identified through the mean linear thermal transmittance. Specifically, the heat transfer coefficient for transmission through the building envelope H_D [W/K] is calculated as the sum of three addends: the one-dimensional losses through the opaque and transparent envelope, the two-dimensional losses through linear thermal bridges

and the three-dimensional losses across the punctual thermal bridge:

$$H_D = \sum A_i U_i + \sum l_j \psi_j + \sum \chi_k \quad (1)$$

where A_i is the dispersing surface of the i^{th} element of the building envelope and U_i its thermal transmittance, l_j is the length of the j^{th} linear thermal bridge with mean linear thermal transmittance ψ_j , and χ_k is the punctual thermal transmittance of the k^{th} three-dimensional thermal bridge.

It should be noted, however, that thermal bridges that result from the intersection of linear thermal bridges are neglected in the calculation of thermal dispersion factor for transmission, in accordance to UNI EN ISO 10211 [3].

The linear thermal transmittance can be defined as:

$$\psi = L_{2D} - \sum U_{1D,i} h_i \quad (2)$$

where U_{1D} is the one-dimensional thermal transmittance of the i^{th} component of the junction, h_i its height and L_{2D} is the linear thermal coupling term obtained from a two-dimensional calculation of the component:

$$L_{2D} = \frac{\phi_{2D}}{T_i - T_o} \quad (3)$$

Where ϕ_{2D} is the real two-dimensional heat flow through the structure, due to the thermal bridges, and T_i and T_o are respectively the indoor and outdoor air temperature.

Hence, the thermal dispersion for transmission through the thermal bridge is:

$$Q_{tb} = \psi l (T_i - T_o) \quad (4)$$

Where l is the length of the thermal bridge.

IV. OPERATIONAL CHARACTERISTICS OF IR THERMOGRAPHY

Infrared Thermography is a non destructive technique applied in a variety of building monitoring: a review of these application is reported in [14].

For quantitative infrared thermography, particular precautions must be observed during a survey campaign, in order to prevent noise, to minimize the sources of error, and to lead a correct interpretation of a thermogram [15].

The main difficulty of "in situ" campaign is connected to non-stationary boundary conditions, mainly due to continuous changes of ambient temperature, which could significantly affect heat transfer through the building envelope. It is therefore preferable to conduct surveys when temperature gradient between inside and outside is at least 12°C (which actually makes the thermographic technique applicable exclusively in the winter months and/or

overnight) and in absence of direct solar radiation, precipitation, and wind (to avoid environmental interference).

It is also important the accurate evaluation of the parameter input to the IR camera, like the emissivity of the wall examined (ϵ_{obj}), the reflected temperature (T_{refl}), the indoor air temperature, relative humidity, and shooting distance.

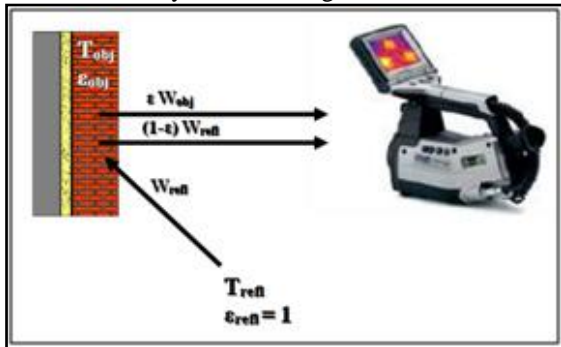


Figure 1. Scheme of the heat exchange process in a shooting with a camera (assuming unitary transmissivity coefficient)

V. EXPERIMENTAL METHODOLOGY

In a recent work, F. Asdrubali, G. Baldinelli, F. Bianchi [12] introduce a new parameter, *the incidence factor of the thermal bridge* I_{tb} , defined as the ratio between the heat flowing in real conditions and the heat flowing in absence of the thermal bridge ("undisturbed area") where the heat flow is monodimensional.

With their experimental methodology, the factor I_{tb} can be calculated by using the information collected by the thermal images of the wall, known the indoor air temperature. With reference to the analysis of the inside of the building envelope during the winter season, this factor can be expressed as:

$$I_{tb} = \frac{Q_{tot}}{Q_{1D}} = \frac{h_{tb,i} A_{pixel} \sum_{pixel=1}^N (T_i - T_{pixel,i})}{h_{1D,i} A_{1D} (T_i - T_{1D,i})} \quad (5)$$

where the subscript "i" stands for "indoor", $h_{tb,i}$ and $h_{1D,i}$ are the internal liminar coefficients of the area close to the thermal bridge and to the "undisturbed area", respectively, A_{pixel} is the area of each pixel of the thermal image, same for all the N pixels, A_{1D} is the overall area through which the two heat fluxes are compared, T_i is the indoor air temperature, $T_{1D,i}$ is the surface temperature of the "undisturbed area" of the wall, and $T_{pixel,i}$ is the surface temperature of each pixel that makes up the thermal image. Since the undisturbed area of the wall and the area near the thermal bridge are captured in the same thermal image and at the same time, liminar coefficients can be considered equal. It

is worth noting that $A_{1D} = N A_{pixel}$, so equation (5) can be eased. In the final form, the incidence factor of the thermal bridge comes out to be dependent exclusively on the indoor air temperature and on surface temperature of the examined area, that is:

$$I_{tb} = \frac{\sum_{pixel=1}^N (T_i - T_{pixel,i})}{N (T_i - T_{1D,i})} \quad (6)$$

Starting from equation (5), it is possible to calculate the contribution of a thermal bridge to thermal losses, simply by noting that:

$$I_{tb} = \frac{Q_{tot}}{Q_{1D}} = \frac{Q_{1D} + Q_{tb}}{Q_{1D}} = 1 + \frac{Q_{tb}}{Q_{1D}} \quad (7)$$

and, therefore,

$$Q_{tb} = Q_{1D} (I_{tb} - 1) \quad (8)$$

Another expression of the incidence factor can be gathered using equation (1) in equation (5), that is:

$$I_{tb} = \frac{\psi + \sum l_i U_{1D,i}}{\sum l_i U_{1D,i}} \quad (9)$$

from which it is possible to obtain the linear thermal transmittance, that is:

$$\psi = (I_{tb} - 1) \sum_i U_i l_i \quad (10)$$

The incidence factor can be also related to the increase of the thermal transmittance of the "undisturbed area", due to the effect of the thermal bridge. Under the assumption of steady-state conditions, it is possible to define an equivalent value of thermal transmittance U_{tb} which includes the contribution of thermal bridges, that is:

$$I_{tb} = \frac{Q_{tot}}{Q_{1D}} = \frac{U_{tb} A}{U_{1D} A} \quad (11)$$

and, as a consequence,

$$U_{tb} = U_{1D} I_{tb} \quad (12)$$

Therefore, in order to calculate U_{tb} , it is necessary to know U_{1D} , which can be estimated through the thermographic technique, according to the methodology proposed by Albatici and Tonelli [7] and already applied in a previous work of the Authors [8]. The thermal transmittance of the considered area can be calculated by applying the energy balance of the wall: the sum of the convective and radiant heat exchanged by the wall toward the outdoor equals the heat flow for conduction from the indoor toward the outdoor, that is:

$$U_{1D} = \left\{ 5.67 \epsilon_{tot} \left[\left(\frac{T_{1D,o}}{100} \right)^4 - \left(\frac{T_o}{100} \right)^4 \right] + 3.8054 \nu (T_{1D,o} - T_o) \right\} \frac{1}{(T_i - T_o)} \quad (13)$$

where the subscript “o” stands for “outdoor”, and all the terms involved can be calculated by using an IR camera, following the procedure explained in [7] and [8].

VI. CASE STUDY

The case study examined is the "Solar House" an old structure of University of L'Aquila, situated in L'Aquila.

The structure underwent a refurbishment, so the opaque envelope is made up of several building materials with different thermal conductivity.

The reference wall chosen was exposed to the NNE, in order to reduce the incidence of solar radiation during thermographic surveys, and three different types of thermal bridges have been studied (Fig. 2):

1. a thermal bridge on the horizontal edge between the wall and the roof (TB1);
2. a vertical thermal bridge on the corner determined by the junction between the NNE wall and the concrete wall exposed to ESE (TB2);
3. an horizontal thermal bridge at the junction between the girder, made of reinforced concrete, and the perforated bricks masonry (TB3).

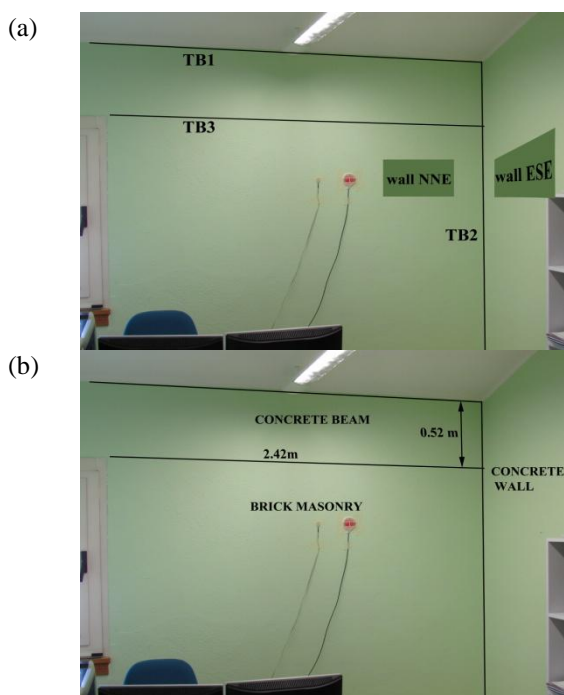


Figure 2. Photograph of the wall studied, with marks on thermal bridges (a) and construction details(b)

In this favorable case, data concerning buildings materials were available, so it was possible to evaluate the thermal transmittance of the concrete beam, of the brick masonry, of the concrete wall and of the roof, applying norm ISO 6946 [16]. Results are summarized in Table 1.

Table 1. U-values of the constructive elements.

Constructive Element	U-value
Concrete beam (cb)	$U_{cb}=0,36 \text{ W/m}^2\text{K}$
Concrete wall (cw)	$U_{cw}=0,36 \text{ W/m}^2\text{K}$
Brick masonry (bw)	$U_{bw}=0,31 \text{ W/m}^2\text{K}$
Roof (r)	$U_r=0,63 \text{ W/m}^2\text{K}$

The thermal transmittance of the “undisturbed” wall (characterized by one-dimensional heat flow) has been evaluated through thermographic technique by measuring the air temperature and external surface temperature of the wall (Fig. 3). The device used was a ThermoCAM S65 HS of Flir System S.r.l. equipped with Focal Plane Array, uncooled microbolometer, 320 x 240 pixel resolution and spectral range from 7.5 to 13 μm [17]. To calculate U_{1D} , equation (12) has been applied, and in order to assess the quality of the results, measurements were repeated in arbitrary days and hours, characterized by significantly different weather conditions. Results are shown in Table 2.

Table 2 Thermal transmittance values calculated in two days of measurement

	T_o [° C]	T_i [° C]	$T_{1D,o}$ [° C]	U [W/m ² K]
March 23rd, 2012	15.10	23.80	16.05	0.328
April 13th, 2012	5.50	23.30	7.56	0.316

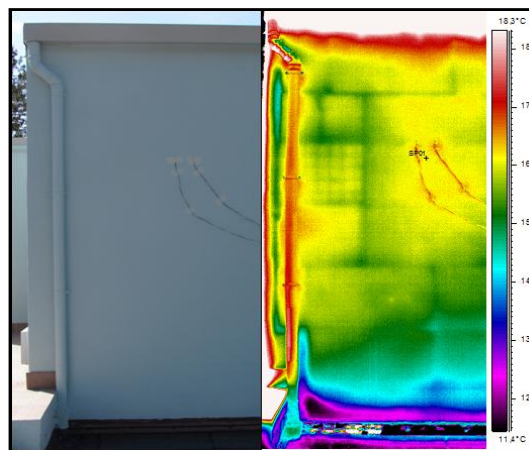


Figure 3. Photograph and thermal image of the outside of the wall studied

Different values were obtained, probably because different weather conditions occurred during measurement campaigns.

Moreover, to validate the thermal transmittance obtained by IR method, a Heat Flow Meter was applied, following the recommendations provided in norm ISO 9869 [18]. The measurement campaign lasted from March, 23rd to March, 27th, and the U-value obtained was 0.37 W/m²K.

Then, a thermal image of the wall has been acquired from the indoor, including the undisturbed area and the thermal bridges (Fig. 4). Even in this case, all the parameters necessary for the application of the thermographic method, like emissivity, temperature, humidity and distance, have been carefully identified and summarized in Table 3.

Table 3 Thermoigrometric conditions of measurement carried on March 23rd, 2012

Recording characteristic	Emissivity	0.93
	Distance	3.3 m
	Recording modality	Standard (IFOV = 1.1 mrad)
Internal thermoigrometric conditions	Temperature	23.8° C
	Relative Humidity	21.6%
External thermoigrometric conditions	Temperature	15.1° C
	Relative Humidity	20%
weather conditions	slightly cloudy sky	

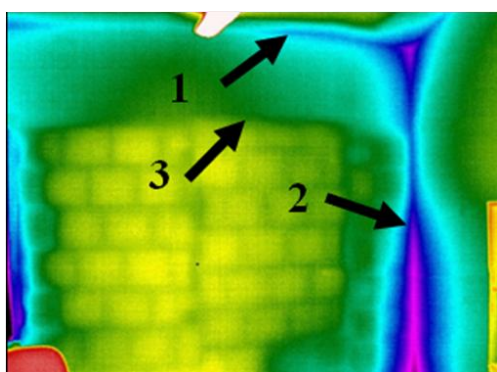


Figure 4. Thermal image of the wall from the inside and tag of the thermal bridges

The thermal image in Fig. 4 highlights other two thermal bridges, not included in the evaluation performed in this work: one near the opening (left side), and a three-dimensional one on the right corner.

The thermal image in Fig.4 shows that the thermal bridges 1(TB1) and thermal bridges 3 (TB3) have a nearly constant temperature field for each

vertical section of the wall, while thermal bridge 2 (TB2) on the vertical edge has a strong variability of thermal field for each horizontal section of the wall.

The different behavior suggested to lead specific analysis and different calculation for each thermal bridge.

Particularly, for TB1 and TB3 it is possible to calculate the incidence factor on a linear domain, while for TB2 it is necessary to introduce a surface domain (Fig.5).

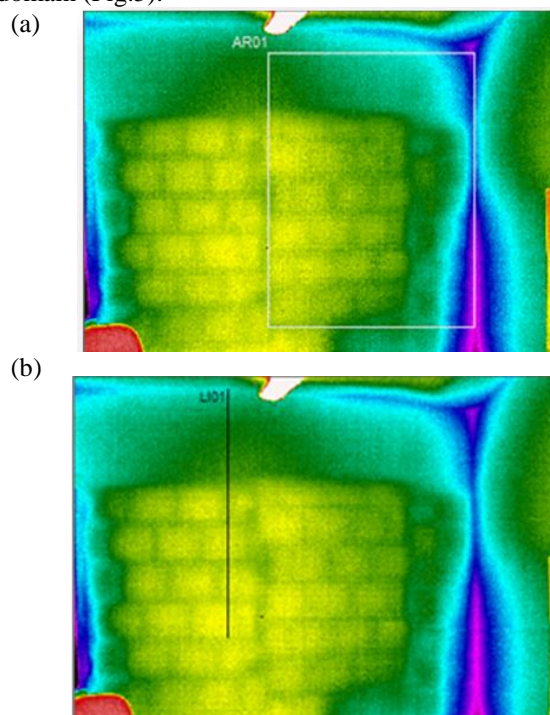


Figure 5. Thermal images of the wall with the superficial domain AR01 for the TB 2 (a) and linear domain LI01 for thermal bridges 1 and 3 (b) .

The linear domain LI01 starts from the corner determined by the junction roof-wall and ends in the brick masonry, 1m far from TB3, in accordance with norm UNI EN ISO 14683 [2].

The surface domain AR01 includes a portion of the brick masonry and the concrete girder, and excludes the horizontal edge of the junction roof-wall, because already taken into account considering the linear domain LI01.

Although norm UNI EN ISO 14683 [2] assumes that the distance of 1 m from the edge is in general sufficient to reach the "undisturbed area", in this the unevenness of the thermal field suggested to extend this length to 1.3 m.

Temperature trends along the linear domain (for TB1 and TB3) and on the surface domain (for TB2) are shown respectively in Fig. 6 and Fig. 7, where the asymptotic temperature reached in the "undisturbed area" is clearly visible and corresponds to 23.32° C in Fig 6, and swinging between 22.6° C

and 23.46° C for Fig.7).

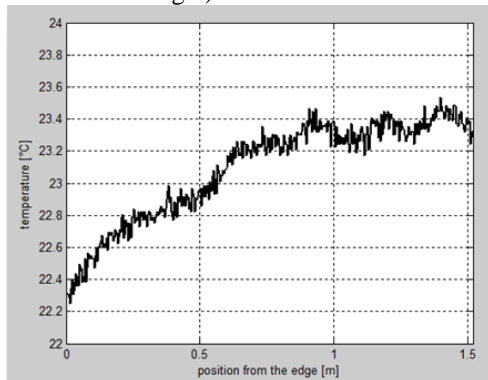


Figure 6. Internal wall surface temperature along the linear domain LI01

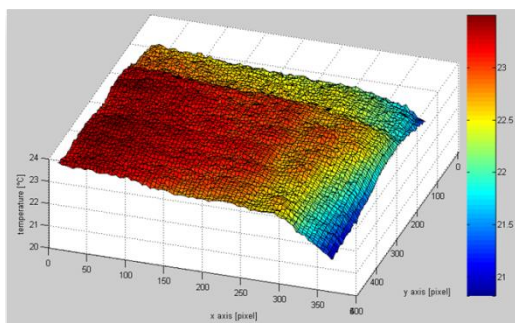


Figure 7. Internal wall temperature on the surface domain AR01

The incidence factor has been calculated using equation (6).

For the linear domain LI01, $I_{tb}=1.464\pm 0.226$, while for the surface domain $I_{tb}=1.590\pm 0.247$.

The uncertainty $\frac{\Delta I_{tb}}{I_{tb}}$, of the order of about 15.5% for both domains, was assessed by applying the formula of propagation of uncertainty according to the UNI CEI ENV 13005 [19] from the definition of the incidence factor, by estimating the uncertainty on the temperature gradient $\frac{\Delta T_i}{T_m}$, assuming from literature that the uncertainty on radiated power $\frac{\Delta W}{W}$ equals 4%:

$$\frac{\Delta T_i}{T_m} = \frac{\frac{\Delta W}{W}}{4\sigma\epsilon T_m^3} T_i \quad (14)$$

A second measurement campaign was carried out on 4/13/2012. Thermoigrometric conditions are listed in Table 4. The incidence factor obtained during this campaign equals, for LI01 1.477 with an uncertainty of 0.235 (15.91%), and for AR01 equals 1.491 with an uncertainty of 0.238 (15.96%).

Table 4. Thermoigrometric conditions of measurement carried on April 13th, 2012

Recording characteristic	Emissivity	0.93
	Distance	4.45 m
	Recording modality	Standard (IFOV = 1.1 mrad)
Internal thermoigrometric conditions	Temperature	23.3° C
	Relative Humidity	29.2%
External thermoigrometric conditions	Temperature	5.5° C
	Relative humidity	63%
weather conditions	clear sky, slightly sunny	

The validation of the experimental method proposed is carried out through numerical calculations using a two-dimensional model.

The software used is "Therm 6.3" [20], a program developed by the Lawrence Berkeley National Laboratory (LBNL) that operates using finite element method. This software allows to analyze the two-dimensional steady-state heat flows through different building components, to determine local transmittance changes due to thermal flows changes and, in addition, it shows the temperature distribution.

The model reproduces the wall and its thermal bridges. Particular attention has been paid to the model of TB2.

In fact, a portion of TB2 is the junction between the concrete wall (wall ESE) and the concrete beam of wall NNE (0.52 m high), while the remaining part is the junction between the concrete wall and brick masonry of wall NNE. This could suggest that TB2 should be modeled as a three-dimensional thermal bridge. However, as shown by the results obtained both by the Thermographic technique and by the numerical simulation, the heat flow is bi-dimensional for TB1 and for the whole beam height (0.52m), and becomes mono-dimensional from TB3 towards the bricks masonry. Therefore it is possible to consider separately the effect of the thermal bridges which are due to different stratigraphy in the same wall.

Cutting plans have been placed at a distance of 1 m from the thermal bridges. Boundary conditions for the model are summarized in Table 5. The results of numerical simulation of the element analyzed in terms of development of isotherms are shown in Fig. 8 and Fig. 9.

Table 5. Boundary conditions set for the numerical simulation

Indoor temperature	20°C
Outdoor temperature	5°C
Liminar coefficient	
Indoor wall	10 Wm ⁻² K ⁻¹
Sloped roof	7.7 Wm ⁻² K ⁻¹
outdoor	25 Wm ⁻² K ⁻¹

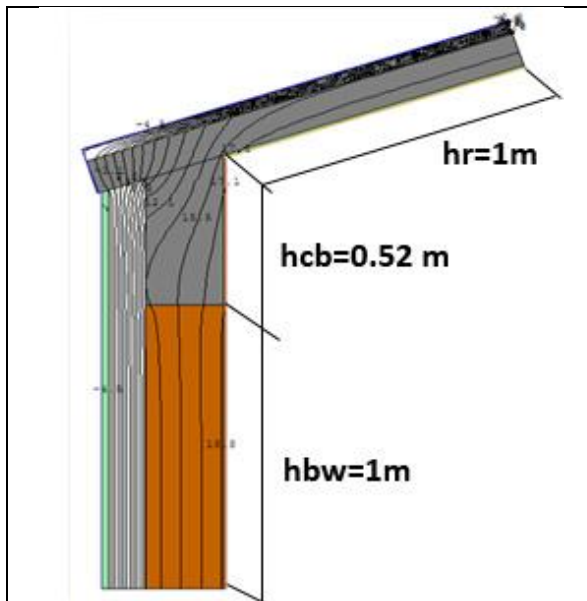


Figure 8. Isotherm displacement obtained by numerical simulation of TB1 and TB3

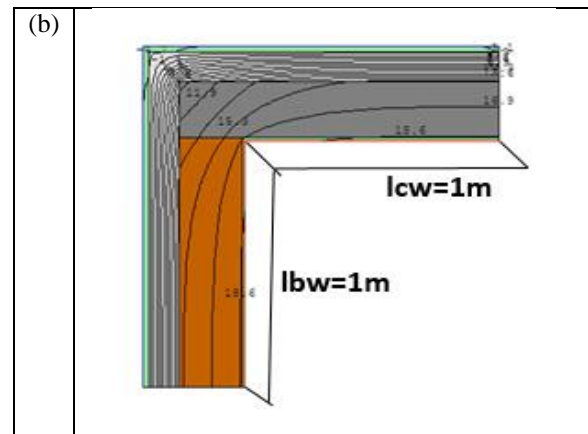
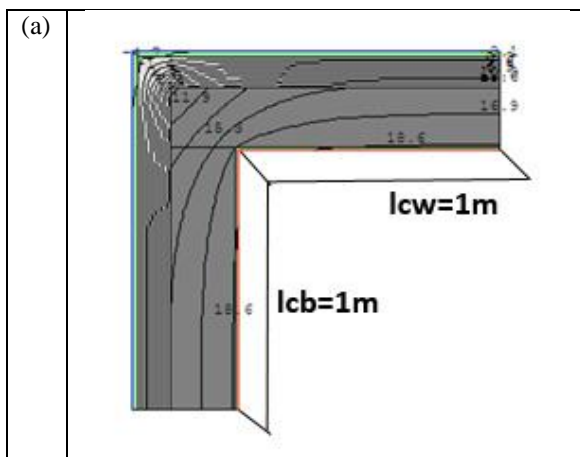


Figure 9. Isotherm displacement obtained by numerical simulation of TB2 at the junction between the wall ESE and (a) the concrete beam ; (b) the brick masonry

The software provides the U_{factor} , which represents the equivalent thermal transmittance of a wall without bridges, so characterized by a one-dimensional heat flow equal to the two-dimensional one that involves the real wall with thermal bridges. The U_{factor} is analogous to the U_{tb} expressed in equation (12). Starting from this parameter, it is possible to calculate the linear thermal transmittance, the incidence factor of the thermal bridge, and to establish a comparison with the value obtained using the Thermographic technique.

For thermal bridges TB1 and TB3 the linear thermal transmittance is:

$$\psi = U_{factor,cw} h_{cw} + U_{factor,cb} h_{cb} + U_{factor,r} h_r - (U_{cw} h_{cw} + U_{cb} h_{cb} + U_r h_r) \quad (15)$$

$$I_{tb} = \frac{U_{cw} h_{cw} + U_{cb} h_{cb} + U_r h_r + \psi}{U_{cw} h_{cw} + U_{cb} h_{cb} + U_r h_r} \quad (16)$$

Where h is the length of integration defined in geometric model, of 1 m for the concrete wall and the roof and 0.52m for concrete beam.

For the thermal TB2, it is necessary to define two different linear thermal transmittances, one for each of the two types of wall interfaces: a linear thermal transmittance between the concrete wall and the concrete beam (equation (17)), and a linear thermal transmittance between the concrete wall and the brick wall (equation (18)).

$$\psi_{cw-cb} = U_{factor,cw} l_{cw} + U_{factor,cb} l_{cb} - (U_{cw} l_{cw} + U_{cb} l_{cb}) \quad (17)$$

$$\psi_{cw-bw} = U_{factor,cw} l_{cw} + U_{factor,bw} l_{bw} - (U_{cw} l_{cw} + U_{bw} l_{bw}) \quad (18)$$

For TB2, the incidence factor can be written as follows:

$$I_{tb} = \frac{1}{U_{eq} A_{tot}} (U_{eq} A_{tot} + \psi_{cw-cb} h_{cb} + \psi_{cw-bw} h_{bw}) \quad (19)$$

where U_{eq} is the thermal transmittance averaged on the areas of each constructive element that makes up the thermal bridge (i.e. the concrete beam and the brick wall), and A_{tot} is the sum of that areas, knowing that that total area A_{tot} is equal to the length l_{eq} of the domain (1.3m in this case) times the whole thermal bridge height (being the latter the sum of the concrete beam and the brick masonry heights).

Therefore, the incidence factor becomes:

$$I_{tb} = \frac{1}{U_{eq} l_{eq}} (U_{eq} l_{eq} + \psi_{cw-cb} \frac{h_{cb}}{h_{cb} + h_{bw}} + \psi_{cw-bw} \frac{h_{bw}}{h_{cb} + h_{bw}}) \quad (20)$$

The incidence factors obtained with the two methods are concordant for both types of thermal bridge, and are shown in Table 6 and Table 7, together with the equivalent thermal transmittance for both the measurement campaign. Deviations between the numerical and experimental method for the two days of measurement are equal to 16.07% and 3.18% 16.81% respectively for TB1 and TB3 and equal to 8.85% and 2.16% for TB2. The incidence factor of the thermal bridge with its field of uncertainty (it is assumed for the numerical method an uncertainty of 5% as ascribed in norm UNI EN ISO 14683) is shown in Fig 10 and Fig 11: results are consistent and prove the correctness of the experimental method proposed.

Table 6. Comparison, in terms of incidence factor and equivalent thermal transmittance, between numerical method and experimental method

		I_{tb}	$U_{tb}[W/m^2K]$
TB1 and TB3	NUMERICAL METHOD	1.2287	0.3856
	EXPERIMENTAL METHOD March, 23 rd , 2012	1.464	0.480
	EXPERIMENTAL METHOD April 13 th , 2012	1.477	0.467
TB2	NUMERICAL METHOD	1.461	0.450
	EXPERIMENTAL METHOD March, 23 rd , 2012	1.590	0.521
	EXPERIMENTAL METHOD April 13 th , 2012	1.492	0.462

It is worth noting that, despite climatic significantly different weather conditions occurred during the two campaigns, results are almost coincident, with differences in percentage terms less than unity.

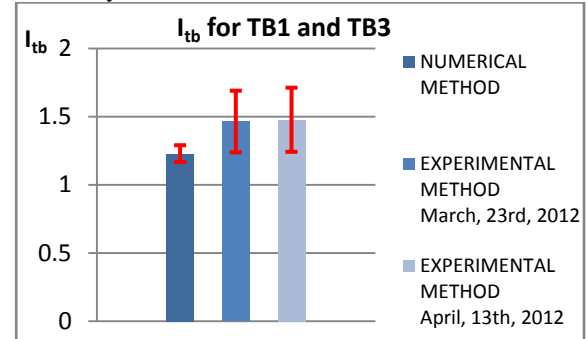


Figure 10. Histograms of the incidence factors obtained, with their uncertainties, for TB1 and TB3.

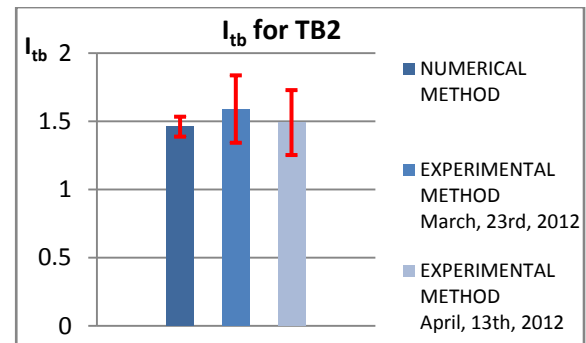


Figure 11. Histograms of the incidence factors obtained, with their uncertainties, for TB2.

Knowing I_{tb} , it is possible to calculate ψ by applying equation (10). Results are shown in Table 7

Table 7. Linear thermal transmittances obtained. Values are expressed in W/mK

	NUMERICAL METHOD	EXPERIMENTAL METHOD March, 23 rd , 2012	EXPERIMENTAL METHOD April 13 th , 2012
TB1 and TB3	0.2587	0.2313	0.2291
TB2 - concrete beam/brick wall	0.189	0.2515	0.2021
TB2 - concrete beam/concrete wall	0.146		

Finally, it is possible to compare the heat loss through the building envelope with reference to the wall and to the three thermal bridges studied (Table

8 shows absolute values and Table 9 shows percentage values). Heat losses are calculated according to equation (4), assuming an indoor-outdoor gradient temperature of 25 K.

Table 8. Heat losses through the wall and through thermal bridges analyzed – absolute values, expressed in W

	NUMERICAL METHOD	EXPERIMENTAL METHOD March, 23 rd , 2012	EXPERIMENTAL METHOD April 13 th , 2012
UNDISTURBED AREA	48,38	51.20	49.32
TB1 and TB3	15,67	13.99	13.86
TB2	6,9	9.56	7.68
TOTAL	70,95	74.75	70.86

Table 9. Heat losses through the wall and through thermal bridges analyzed – percentage values

	NUMERICAL METHOD	EXPERIMENTAL METHOD March, 23 rd , 2012	EXPERIMENTAL METHOD April 13 th , 2012
UNDISTURBED AREA	61.14%	68.49%	69.60%
TB1 and TB3	22.08%	18.71%	19.56%
TB2	16.78%	12.8%	10.84%
TOTAL	100%	100%	100%

In detail, heat losses due to TB1 and TB3 calculated with the experimental method are smaller than the ones calculated with the numerical method, while heat losses due to TB2 estimated through the experimental method are higher than the result of the numerical method, probably because of the complexity of the thermal field detected with the IR camera.

However, as shown in Table 9, percentage heat losses due to thermal bridges obtained through experimental method are smaller, because of the higher thermal transmittance of the undisturbed area estimated experimentally.

VII. CONCLUSION

The inadequacy of the simplified methods of calculating thermal bridges on the one hand, the high execution times and the need for an exact knowledge

of construction details required by numerical calculations of the other hand, together with the need to employ measurement techniques of thermal transmission properties of building elements offer quantitative infrared thermography as a simple and effective means of evaluating the transmission losses through the thermal bridges.

From the knowledge of the internal air temperature and surface temperature distribution of the wall, obtained by thermographic recovery, the incidence factor of the thermal bridge can be evaluated. This parameter, which describes quantitatively the dispersion introduced by the thermal bridge, represents the percentage increase of thermal transmittance of wall analyzed considering the effects of thermal bridge with respect to the transmittance of the undisturbed wall.

The comparison of the experimental results obtained with the use of infrared thermography and numerical calculations carried out using software that operates according to the finite element method, on the one hand, confirms the validity of the experimental method proposed, underlining how the incidence factor of the thermal bridge is one parameter representative of actual losses through the thermal bridges, on the other hand highlights as, in real cases, the thermal field in building structures differs significantly from the theoretical behavior with temperature gradients not foreseen by numeric computations.

In conclusion, despite the quantitative infrared thermography is a technique still in experimental stage, whose biggest issues to overcome are the variability of the results linked to many parameters, the need for certain operational conditions that make correct measurements done only during the winter months and the uncertainty of measurement still too high (15%), it can be considered as an effective assessment tool of the behavior of materials and structures from an energetic standpoint. And whilst mistakes can be a non-negligible extent, the high accuracy of the results obtained by numerical methods must always be adjusted to the condition of being a purely theoretical calculation that does not match the actual behavior of materials.

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