Numerical Analysis of Thermal Bridges in Dynamic Conditions

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Abstract

Thermal bridges play a significant role in the heat loss of nearly Zero Energy Buildings (nZEB). In the case of existing buildings, the underestimation of thermal bridges can lead to errors of about 20 % in the assessment of their energy requirements.
Nowadays, proper simulation tools for evaluating the building energy performance in dynamic conditions are increasingly needed. Their outputs are important inputs for life cycle costs (LCC) and life cycle assessment (LCA) as well as for energy audits. A weak point is that the tools which are currently well established on the market, do not consider the contribution given by thermal bridges to the overall building energy balance as they rely on a one-dimensional approach to recreate heat flows.
Several scientific studies deal with different methods that can be applied to evaluate the dynamic behaviour of thermal bridges, but they disregard the wall capacity to accumulate/release heat loads and the role played by internal temperatures.
This work analyses some numerical methods proposed by different authors based on the discretization of thermal bridges and their characterization in dynamic regime.
A calculation procedure is evaluated to underline its potential as a rapid dynamic calculation algorithm to be integrated in the current software for dynamic analyses. The surface temperatures and the heat fluxes are taken into account.
In the present work, the method of the equivalent thermal wall has been implemented to get the input parameters required to dynamically assess the thermal bridges energy contribution. Afterwards a finite volume analysis is developed to compare the outputs coming from different methods in terms of crossing fluxes, surface temperatures and thermal storage capacities.
A low percentage error is found between the equivalent thermal wall and the real one in terms of surface temperatures. This achievement allows to carry out proper superficial condensation assessments.
Anyway the above-exposed procedure is quite complex and time-consuming. The algorithm is then expected to be refined in the future by simplifying the necessary operations for the evaluation of thermal bridges.

1. Introduction

The Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010, on the energy performance of buildings (EPBD Recast) has established a common framework of measures for the promotion of energy efficiency within the Union in order to ensure the objectives of the "climate-energy package 20/20/20."
Buildings account for about 40 % of total energy consumption in the Union (Ascione et al., 2012) it is necessary to reduce their greenhouse gas emissions by using energy from renewable sources and by reducing energy consumption in the buildings sector.
Italy, under the existing rules, has issued a new Ministerial Decree on June 26, 2015 for the energy efficiency of buildings. The decree imposes more restrictive limits than before in order to achieve nearly Zero Energy Buildings (nZEB).
Designers can use two main approaches for building energy calculation: a simplified approach and a dynamic simulation.
The first is based on UNI EN ISO 13790:2004 (Thermal performance of buildings - Calculation of energy use for space heating) developed according

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to the European Energy Performance of Buildings Directive (EPBD- Directive 2002/91/EC).

This standard proposes a quasi steady-state approach based on algebraic equations. Heating and cooling energy demands are calculated on the basis of a balance between the transmission and ventilation heat losses, and the internal and solar gains.

The simplified calculation has several advantages over the dynamic approach because it is simpler and more intuitive, but it is considered insufficient to properly describe the dynamic behaviour of the building envelope and its system controls (Kim et al., 2013).

The dynamic approach is preferable to design high-efficiency buildings. It requires extensive inputs and the correlation between inputs and outputs is often not intuitive, but it has relevant advantages. Designers have a high level of modeling possibilities for the integrated performance assessment. In addition, simulations in dynamic regime give more precise outcomes.

Anyway it is necessary to underline the importance of the contribution of thermal bridges on energy demands, whatever simulation method is used.

According to the International Standard EN ISO 10211/2008, a thermal bridge is "a part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, and/or a change in thickness of the fabric, and/or a difference between internal and external areas, such as occur at wall/floor/ceiling junctions". Numerically, it is estimated that thermal bridges can increase the thermal loads and needs of a building up to 20 % (Ascione et al., 2012). Other authors showed that, under certain conditions, neglecting thermal bridges can lead to errors on energy needs calculation over 40 % (Kosny et al., 2002).

A proper correction or elimination of thermal bridges is hardly achievable. In nZEB, where a great envelope thermal resistance is advisable, thermal bridges play a significant role.

In the quasi steady-state approach, proposed by the recent Italian decree, the value H'_T has been introduced. It represents the average value of the envelope's thermal transmittance that is the sum of transparent and opaque surfaces' thermal transmittances, including thermal bridges (UNI EN ISO 6946: 2008; UNI EN ISO 14683: 2008). Previous studies have demonstrated that in order to reach the actual targets established for H'_T by the Italian law, the designer needs to plan a building envelope with very small thermal transmittance in order to balance the heat loss through thermal bridges.

On the other hand, in the dynamic approach, the impact of thermal bridges has not been properly calculated yet. Dynamic simulation programs, as EnergyPlus™, adopt a zero-dimensional analysis that assumes a constant indoor air temperature. Many authors have published studies proposing several methods for the analysis of thermal bridges, according to both statistical and numerical approaches (Ascione et al., 2014; Seem et al., 1989; Renon, 2002).

An option consists on using a specific software for the calculation of thermal bridges that considers them as a linear heat transfer resistance (i.e. THERM or KOBRA).

Another possibility is to use numerical methods programs, but the computational effort increases (e.g., COSMOS, Fluent, Femlab). These programs can be used for calculating any type of thermal bridge without implementing them in the building.

In this paper, a finite volume method is compared with the "equivalent wall method" developed by Kossecka and Kosny (Kossecka et al., 1997; Aguilar et al., 2014), for modelling the effects of thermal bridges on buildings. This method allows to include thermal bridges in dynamic simulation programs for the whole building energy assessment: once the equivalent wall has been calculated, it has to be included in place of the real wall.

2. Equivalent Thermal Wall Concept

The equivalent thermal wall concept allows to switch from a thermal bridge to a thermally similar wall made of three layers, obtained through the following steps:

1) get the temperature distribution and wall heat fluxes from the solution of the steady-state heat conduction problem through Fourier equation;

2) calculate the dimensionless factor φ (through the method of Kossecka and Kosny);
3) obtain the equivalent thermal properties (thermal capacity C, thermal resistance R, density ϱ, thermal conductivity λ) with an iterative algorithm.

2.1 Boundary Conditions

This work considers a two-dimensional typical problem of thermal bridge. The heat transfer is based on the Laplace equation in (1).

Usually, energy simulation software implement one-dimensional operations for the energy balance: starting from the Laplace equation in 2D, through the decomposition of the thermal bridge, the geometric node of the structure is simplified into parts with the advantage of having a one-dimensional heat flow in each.

The boundary conditions taken into account are convection and radiation; on the sides a temperature difference of 1 K is set (2), on the interfaces the elements have the same temperature and heat flux (3).

$$\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} = 0 \qquad (1)$$

$$\left.\begin{aligned} -\lambda_e \frac{\delta T}{\delta \eta} &= \frac{1}{R_e}(T_e - T_{W,e}) \\ -\lambda_i \frac{\delta T}{\delta \eta} &= \frac{1}{R_e}(T_i - T_{W,i}) \end{aligned}\right\} \qquad (2)$$

$$T_i = T_j\,;\ -\lambda_1 \frac{\delta T}{\delta \eta} = -\lambda_2 \frac{\delta T}{\delta \eta} \qquad (3)$$

2.2 Approach and Finite Difference Method

The study needs the use of a simple calculation software (as a spreadsheet), in which the thermal bridge is discretized into elements in the steady-state heat conduction problem, or Computational Fluid Dynamics programs (CFD) where the analysis is launched in transient conditions.

The technique of finite differences is considered for the conduction heat transfer in 2D:

- each node represents the temperature of a point on the surface considered;
- temperature at the node represents the average temperature of that region of the surface;
- algebraic expressions are used to define the relationship between adjacent nodes on the surface;
- by increasing the number of nodes on the surface it is possible to increase the spatial resolution of the solution and potentially increase the accuracy of the numerical solution, however this increases the number of calculations needed to obtain a solution to the problem.

The diagram in Fig. 1 represents the differential temperature increase compared to the spatial coordinates; it also expresses the first balancing law for volume control.

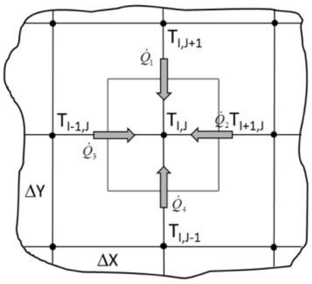

Fig. 1 – Differential temperature increases

2.3 Exemplary Case (Wall Corner)

The thermal bridge analysed for the method validation is a corner originated by two multi-layer walls with a concrete pillar (typical mid XX century building, Fig. 2). The outside surfaces are in contact with the outdoor environment with a conventional temperature T_e=1 °C, while internal surfaces face an indoor conventional temperature T_i = 0 °C.

Materials and thermal properties of each component of the thermal bridge are included in Table 1.

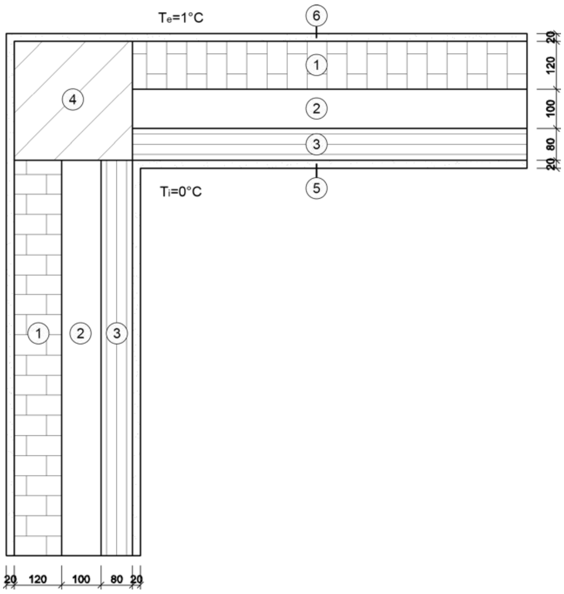

Fig. 2 – Layers of thermal bridge originated by two walls with pillar

Table 1 – Building materials and thermal properties of the corner

	Material	ϱ [kg/m³]	C_P [J/(kg K)]	λ [W/(m K)]
1	Solid brick	900	1000	0.512
2	Air gap	1.2	1000	0.026
3	Hollow brick	630	1000	0.212
4	Concrete pillar	1090	1000	1.22
5	Interior plaster	1150	1000	0.57
6	Exterior plaster	1150	1000	0.57

Concerning the corner section, it is very important to delete the node resulting from the intersection of the two walls to obtain a mono-directional heat flow, following few geometric guidelines. It is important to note that when isolines become perpendicular to the section, the thermal bridge influences the finish area. The study is carried out with a distance of up to 1m from the intersection of the two wall blocks.

Therefore, the following lengths are defined and summarized (Fig. 3): L1/2: 1.0 m; N1/2: 0.2 m; W1/2: 0.8 m (L1/2 – N1/2); A1/2: (0.2 m²).

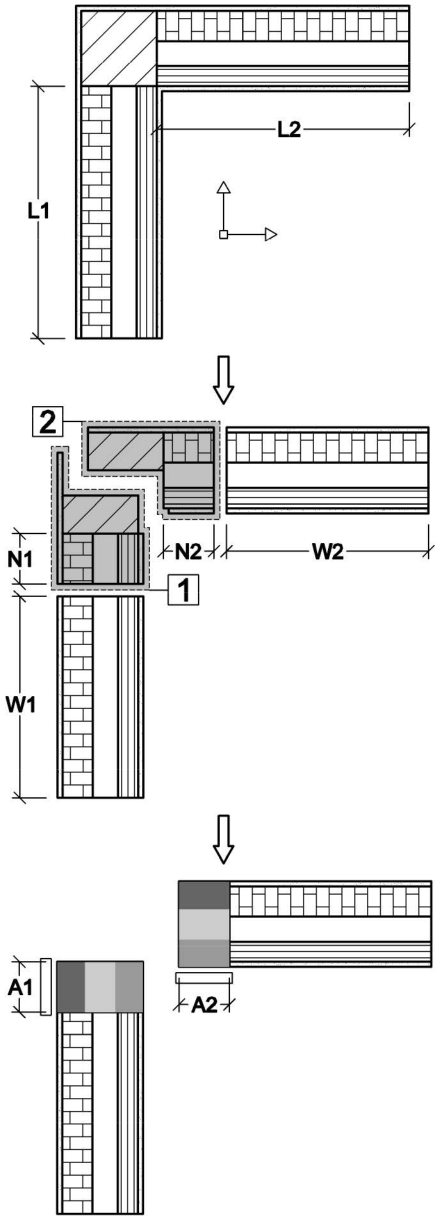

Fig. 3 – Decomposition of the thermal bridge in the equivalent thermal wall with indexes

2.4 Definition of Temperatures and Dimensionless Factors

In accordance with the above considerations regarding the discretization of the nodes by a finite difference method, an Excel matrix is developed (Fig. 4) in which each node is represented by a temperature value.

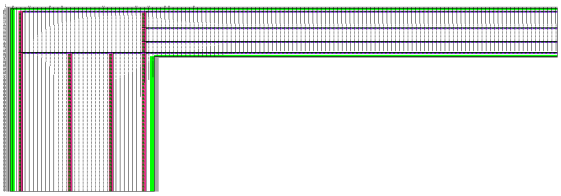

Fig. 4 – The thermal bridge model set out in Excel with highlighted board and interface cells

All links of the mesh are 1 cm x 1 cm squares; the intersections of the plot lines are the nodes, the points where the temperatures are calculated. All nodes are interconnected by equations so that the result is a set of simultaneous equations equal to the number of nodes; the number of unknown factors is the same of the equations. When the number of nodes grows, the size and complexity of the system increases.

Being the heat capacity C (4), after calculating the flow Q [W] in the external/internal interfaces as the sum of specific flows in each row or column of the spreadsheet, we proceed to the determination of dimensionless factors φ_{ii}, φ_{ee}, φ_{ie} (5).

$$C = \int \rho C_p dV \qquad (4)$$

$$\left.\begin{aligned} \varphi_{ii} &= 1/C \int \rho C_p (1-T_n^2) dV \\ \varphi_{ee} &= 1/C \int \rho C_p T_n^2 dV \\ \varphi_{ie} &= 1/C \int \rho C_p T_n (1-T_n) dV \end{aligned}\right\} \qquad (5)$$

The following condition must be satisfied:

$$2\varphi_{ie} + \varphi_{ii} + \varphi_{ee} = 1 \qquad (6)$$

It is very important to define the geometry of the portion of the thermal bridge that will refer to the defined equivalent thermal wall.

2.5 Algorithm Development

From the heat capacity C, the dimensionless factors and the thermal transmittance U (7) it is possible to get thermal variables (Cm, Rm, ϱm, λm) of the three layers of equivalent thermal wall, where m = 1, 2, 3. Some equations, expressed by Kossecka and Kosny (8) rule the method. The aim is to find the thermal resistance of the external layer R1 to which the heat capacity C2 of the intermediate level is close to zero but positive. A set of calculations has been improved to get to the solution faster (Table 2) assuming a fictitious α value (0.1-0.3).

$$U = Q/(A \cdot \Delta T) \qquad (7)$$

$$\varphi_{ii} + \varphi_{ie} = \frac{1}{RC} \sum_{1}^{3} C_m \left(\frac{R_m}{2} + R_{m-e} \right) \qquad (8)$$

$$\phi_{ie} = \frac{1}{R^2 C} \sum_{1}^{3} C_m \left(\frac{-R^2{}_m}{3} + \frac{R_m R}{2} + R_{i-m} R_{m-e} \right) \qquad (9)$$

$$R = \sum_{1}^{3} R_m \qquad (10)$$

$$C = \sum_{1}^{3} C_m \qquad (11)$$

Table 2 – Scheme for the calculation of the thermal properties

R_T	1/U		
j=	1	j=	1+j
$R_{1,min}$	0.01	$R_{1,min}$	0.01
$R_{1,MAX}$	0.01	$R_{1,MAX}$	$R_{1,j-1} \cdot \alpha$
$R_{1,j}$	$(R_{1,min}+R_{1,MAX})/2$	$R_{1,j}$	$(R_{1,min}+R_{1,MAX})/2$
$R_{2,j}$	R_T-Rs-R_1,j-R_3,j	$R_{2,j}$	R_T-Rs-R_1,j-R_3,j
$R_{3,j}$	$(R_{1,min}+R_{1,MAX})/2$	$R_{3,j}$	$(R_{1,min}+R_{1,MAX})/2$

Finally, the properties of the equivalent thermal wall are calculated (Tables 3 and 4).

Note that a standard value is considered for the specific heat for the three layers C_P = 1000 J/(kg K) whereas, regarding the thickness e (m) of the layers, it is a third part of the equivalent wall thickness.

Table 3 – Thermal variables of the three layers in the equivalent thermal wall

Layer m	R (m^2K/W)	Cm ($kJ/(m^2K)$)	e (m)	ϱm (kg/m^3)	λm (W/(mK))
Se	0.04				
1	0.165	68.456	0.11	622.33	0.667
2	2.390	0.101	0.12	0.84	0.050
3	0.165	418.013	0.11	3800.12	0.667
Si	0.13				
Σ	2.8902	486.6	0.34		

Table 4 – Thermal transmittance and dimensionless factors for the equivalent thermal wall

Q [W]	U [W/m^2K]	φ_{ii}	φ_{ee}	φ_{ie}
0.346	0.3460	0.738	0.134	0.064

3. Results

With a Computational Fluid Dynamics program, two simulations are launched, with the same boundary conditions first through the thermal bridge, then in an equivalent thermal wall (the section is specular) in dynamic conditions. The results are extracted and compared in some graphics.

3.1 Method Validation

The geometric model and mesh are defined using a CAD pre-processor (Fig. 5); the idea is to draw the thermal bridge by dividing it into mesh and having the *.msh file read by a CFD software to solve the heat transfer equations.

The first simulation is a steady-state heat conduction analysis carried out to obtain the temperature field and the heat fluxes, in order to better compare the values of the flows and to determine the isolines where the flow is one-dimensional.

After that the final simulation is in transient regime by applying a 20 K temperature difference between environments: inner temperature is fixed a constant; instead the external air temperature changes with a sinusoidal profile. The indoor temperature is a fixed constant $T_i = 20$ °C, the law for outside temperature is $T_e(t) = F\sin(\omega t)$ where the amplitude F = 5 °C and the period $T = 2\pi/f = 24$ h.

The results are repeated in the same way already after about 12 hours; thus, generally the simulations will run for a period of 2 days to make it independent from the initial conditions.

3.2 Discussion

Some Iso-Surfaces are created to determine the temperature on time throughout the section thickness. The Iso-Surfaces considered are: y = 0.0 m; y = 0.4 m; y = 0.8 m; y = 0.9 m.

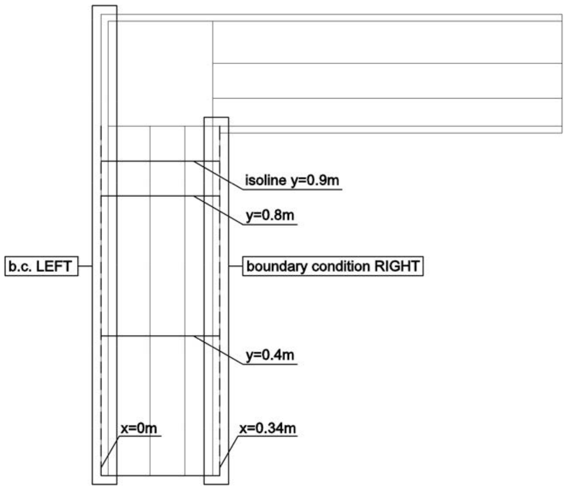

Fig. 5 – Schematization of the thermal bridge with relative nomenclature

The temperature profile of each Iso-Surface is traced by placing it in a defined point (Fig. 6), such as the simulation of the 24th hour of the second day). It can be noted that close to the thermal bridge (y = 0.9 m), the line has a different trend as influenced by the node (a). On the contrary, in the case of the equivalent wall, there are no differences in the temperature profiles based on their location because there is not a two-dimensional flow (b). Trying to overlap two graphs of the same Iso-Surface (y = 0.8 m), the surface temperatures are exactly the same, as opposed to the internal temperatures that show a different behavior (c).

Internal temperatures are different because the three equivalent layers are assumed constant but we need to consider the permeability factor; the hygrometric aspect is not to be considered for the variations of interstitial condensation. Simulations includes 24 consecutive analyzes, setting always the Time Step at 600 s, but changing the Number of time steps from 150 to 288 (simulations every hour from the 25th to the 48th); the temperature profiles on Iso-Surface are extrapolated at various distances from the bottom left point, considered the origin of the Cartesian axes.

When comparing the graphics of the middle Iso-Surface (y = 0.9 m) (Fig. 7); note that the two graphs do not differ particularly, less than a small margin.

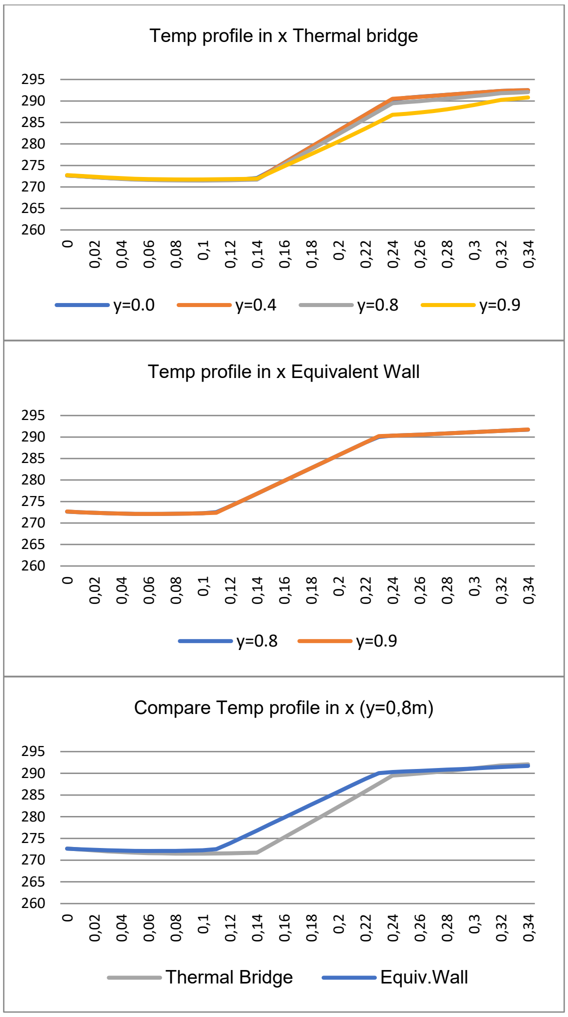

Fig. 6 – Temperature profile x-axis of thermal bridge (a), equivalent wall (b) and comparison (c)

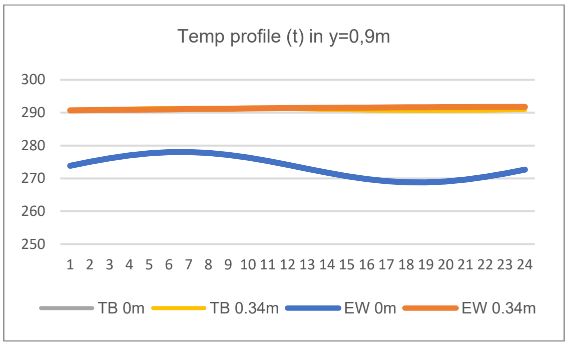

Fig. 7 – Trends of surface temperatures of the left and right boundary conditions, of the thermal bridge and the equivalent wall respectively.

When analyzing the heat flow trend in time (Fig. 8) the uncertainty on the total value is undefined, but there is a non-negligible error.

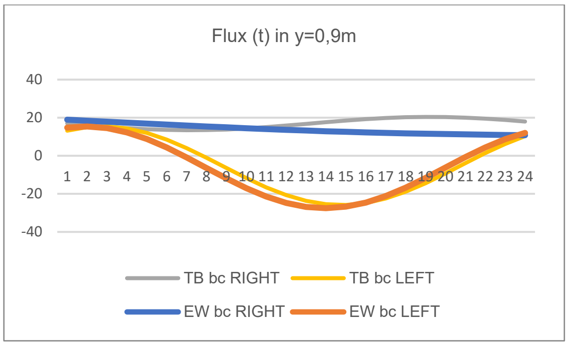

Fig. 8 – Uncertainty on heat flow trend

4. Conclusion

This paper presents the decomposition methodology of a thermal bridge that can be used to treat any type of thermal bridge which can be inserted into a dynamic modeling software for the calculation of the dispersions for transmission in dynamic regime. A good accuracy regarding the surface temperatures has been proved, therefore the method can be used effectively for energy assessments. This allows to evaluate the incidence of the thermal bridges, in winter and in summer, on a low-energy building and then to analyse their impact in terms of energetic consumption. Obviously, this method can be used only if there is a software development: it should be possible to automatically insert the geometries of thermal bridges to make their discretization faster.

Nomenclature

Symbols

A	Reference area for 1m depth (m^2)
C	Heat capacity (m^2 kg/W)
C_p	Specific heat (J/(kg K))
e	Thickness of layer (m)
L	Length of wall (m)
N	Distance between the point where the vectors of the heat flux are not perfectly perpendicular to the first/second wall and the thermal bridge node (m)
Q	Heat flow (W)
R	Thermal resistance (m^2 K/W)

T	Temperature (°C or K)
Tn	Temperature in a node (K)
t	Time (s)
U	Thermal transmittance (W/(m^2 K))
V	Volume (m^3)
W	Length of first/second wall affected by a mono-directional flow (m)
α	Fictitious value
λ	Thermal conductivity (W/(m K))
ρ	Density (kg m^3)
φ	Dimensionless factor

Subscripts/Superscripts

bc	Boundary condition
e	External
EW	Equivalent wall
i	Internal
m	m-th layer
TB	Thermal bridge
W	Wall

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