Dynamic Simulations for Inhomogeneous Components

Giorgio Baldinelli¹, Francesco Bianchi², Agnieszka Lechowska³, Jacek Schnotale³

¹University of Perugia - Department of Engineering, Perugia, Italy

²CIRIAF, Perugia, Italy

³Cracow University of Technology - Institute of Thermal Engineering and Air Protection, Cracow, Poland

Abstract

For highly inhomogeneous components (windows, doors, etc...), imposing sinusoidal temperatures from one side and constant temperature to the other side, could give periodic thermal transmittance exactly with the same definition described in the standard EN 13786. For thermal bridges something similar to the ψ value of steady-state conditions could be defined: the idea is that a homogenous wall as its own periodic thermal transmittance; when a thermal bridge is applied to this wall (for instance with the insertion of a pillar), the simulation will give a new periodic thermal transmittance. The difference between the two periodic thermal transmittances gives information on the effect of the thermal bridge, obtaining something similar to the ψ value. With a Computational Fluid Dynamic analysis, the paper deals with the definition of linear periodic thermal transmittance that could be useful for the response of the whole building envelope (in terms of complex heat flow rate through the inner environment) to the external temperature oscillation. This approach opens the way to define a new Standard to include thermal bridges and inhomogeneous components in general in the dynamic calculations of the buildings envelope.

Introduction

The climate changes require measures to reduce polluting emissions and greenhouse gas emissions. To achieve this aim, the building design process has to take into account energy efficiency aspects of the building envelope.

The building envelope is the interface between the external environment and the conditioned indoor environment; elements of discontinuity, such as windows and thermal bridges, are among the main causes of heat dispersion. In the design phase, the evaluation of the influence of thermal bridges helps to better represent what actually happens, since their presence accounts for over 30% of the total heat loss (Gao et al., 2008). The technical regulations on the calculation of thermal bridges are based on the steady-state conditions hypothesis, with temperature not variable over time (ISO 10211, ISO 14683), without taking into account the thermal inertia of the different components. In the real world, the temperature outside a building varies at first approximation periodically over

the course of the day, with a sinusoidal trend, while it results reasonable to consider inside an almost constant temperature, by means of air conditioning systems.

Homogenous multilayer walls are analysed under periodic boundary conditions with the procedure described in the Standard ISO 13786; the specific heats, and the material densities play a role that was not significant in steady-state conditions. Inhomogeneous components, such as thermal bridges, cannot be treated with same instruments, therefore, a different approach is needed.

Dynamic models are necessary to get precise evaluations for thermal bridges; keeping the same outcomes of the Standard ISO 13786, the effort to reach high amplitude attenuation values affects the choice of materials, while the achievement of a proper phase shift helps to define and optimize the control strategy (Martin et al., 2011).

Literature review

Mao and Johannesson (1997) proposed dynamic models to evaluate the performance of thermal bridges with a frequency response method. The thermal bridge is divided in finite elements to express the temperature in each node as complex number in terms of amplitude and time shift related to the temperature oscillations.

Gao et al. (2008) developed a low-order model of heat transfer for the extra-flux due to 3D thermal bridges. The method divides thermal bridge in finite volumes to create a state space matrix to express the output as a vector correlated with temperature and input data. The method allows to drastically reduce the time of calculation not to consider 3D configurations. The thermal losses through the envelope can be evaluated as sum of thermal losses of one-dimensional elements and extra-flux for the thermal bridge considered like a fictitious component by means of the space state matrix.

Martin et al. (2011) show the problems related to the dynamic characterization of thermal bridges. To show the critical point of this analysis, the authors analyse with a dynamic study, two different types of thermal bridge: one with similar inertia to the homogenous wall and the other when the thermal bridge has a much lower inertia.

Tadeu et al. (2011) applied a Boundary Element Method BEM in the frequency domain to study the dynamic behavior of thermal bridges. The solutions have been obtained by means inverse FFT (Fast Fourier Transform)

to simulate the external temperature oscillation. The BEM has been validated with experimental analysis that showed good agreement with numerical analysis.

Aguilar et al. (2014) and Martin et al. (2012) implemented the method of equivalent wall to characterize the thermal bridge. The thermal bridge can be substituted by an equivalent stratigraphy that behaves like it. The simplification of a complex geometry with a one-dimensional wall make the dynamic analysis more feasible.

Ascione et al. (2014) proposed a validation of a numerical model (Matlab environment) for bidimensional thermal bridge heat transfer conditions in transient regime. The model is validated through a comparison with experimental data conducted on a L-shaped thermal bridge. The paper reports a good agreement between experimental and numerical analysis.

Viot et al. (2015) proposed a review of the main calculation methods both on steady-state and dynamic regime for the wood frame construction. Collecting models from the most recent works, the authors apply them to two classical wood construction thermal bridges: wood pillar and wall-to-wall junction. The review shows the complexity of thermal bridge analysis defining "heavy work" the detailed integration of specific configuration of thermal bridge into a building energy performance simulation tool.

Finally, Martin et al. (2012) compared the experimental results of dynamic behaviour of thermal bridge studied in a guarded hot box, with numerical analysis. The configurations with and without thermal bridge have been studied, showing an error lower than 2% between the two methods.

Methods

The thermal bridges effect is considered, in the overall steady-state energy balance of the building envelope, by mean the following equation (ISO 14683):

$$\Phi = H_T \cdot (\theta_i - \theta_e) \quad (1)$$

Where:

Φ thermal flux [W];

θ_i e θ_e are the internal and external temperatures, [K];

H_T is the heat loss coefficient of the building envelope, [W/K].

H_T , in turn, is composed by several terms that represent the dispersion through the building envelope, the terrain and the non-heated room. The dispersion through building envelope L can be defined by the following equation (ISO 14683):

$$L = \sum U_i \cdot A_i + \sum \psi_k \cdot l_k + \sum \chi_j \quad (2)$$

Where:

U_i is the thermal transmittance of the element i of the building envelope [W/m²K];

A_i is the surface of the element i of the building envelope [m²];

ψ_k is the linear thermal transmittance of thermal bridge k [W/mK];

l_k is the length of thermal bridge k [m];

χ_j is the point thermal transmittance of point thermal bridge j [W/K].

According to the standard ISO 10211 the linear thermal transmittance of thermal bridge can be evaluated by simulations of the 2D model of the structure. The energy behaviour of the thermal bridge gives the information on the flux flowing through the real structure (L^{2D}). The linear thermal transmittance can be calculated with the following equation:

$$\Psi = L^{2D} - \sum_{j=1}^N U_j \cdot l_j \quad (3)$$

Where:

L^{2D} is the linear thermal coupled coefficient of the thermal bridge structure, [W/mK];

U_j is the linear thermal transmittance of one-dimensional element j, [W/m²K];

l_j is the length of the one-dimensional element j, [m].

The Ψ value represents the principal index of the steady-state evaluation of thermal bridge effect in the building envelope. It can be retrieved by numeric analysis and thermal bridge abacus (ISO 14683). The numeric analysis allows to obtain the lowest uncertainty using a model that represents the real structure. The Ψ value well describes the energy behaviour of thermal bridges during winter season, where the steady-state hypothesis can be applied. It represents the extra-flux that passes through the envelope caused by the singularity (thermal bridge).

During the warm season the sinusoidal behaviour of the external temperature does not match with steady-state hypothesis and the linear thermal transmittance gives a wrong estimate of the thermal bridge behaviour (Tadeu et al., 2011)

Considering the one-dimensional wall, its behaviour in the non-steady state model, is well described by the periodic thermal transmittance, that can be evaluated with the standard ISO 13786. Temperatures and thermal fluxes are represented around their long term average values by a sinusoidal function of time:

$$\theta_n(t) = \bar{\theta}_n + |\hat{\theta}_n| \cos(\omega t + \varphi) \quad (4)$$

$$q_n(t) = \bar{q}_n + |\hat{q}_n| \cos(\omega t + \varphi) \quad (5)$$

$\bar{\theta}_n$ and $\bar{q}_n$ represent the average value of temperature and heat flow. The sinusoidal functions can be expressed by complex numbers, defining the complex amplitudes of the variations with the following expressions, respectively for the temperature and heat flow:

$$\hat{\theta}_{\pm n} = |\hat{\theta}_n| e^{\pm i\varphi} \quad (6)$$

$$\hat{q}_{\pm n} = |\hat{q}_n| e^{\pm i\varphi} \quad (7)$$

The dynamic thermal properties of the multilayer one-dimensional wall can be calculated from the complex amplitude. The periodic thermal transmittance is a complex quantity defined as "the complex amplitude of the density of heat flow rate through the surface of the

component adjacent to zone m , divided by the complex amplitude of the temperature in zone n when the temperature in zone m is held constant" (ISO 13786). The following equation, together with the figure, expresses the concept of periodic thermal transmittance.

$$\hat{Y}_{mn} = \frac{\hat{q}_m}{\hat{\theta}_n} \quad (8)$$

Figure 1: Schematic representation of the periodic thermal transmittance.

The standard ISO 13786 defines the heat transfer matrix of a building component to link the complex amplitude of temperature and heat flow on both sides of the element:

$$\begin{Bmatrix} \hat{\theta}_2 \\ \hat{q}_2 \end{Bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{Bmatrix} \hat{\theta}_1 \\ \hat{q}_1 \end{Bmatrix} \quad (9)$$

Each element Z_{xy} of the heat transfer matrix is a function of thermal and geometrical properties (density, specific heat, thermal conductivity and thickness) of each layer that composes the multilayer wall. By means the knowledge of the heat transfer matrix of a building component, the periodic thermal transmittance can also be expressed as follows:

$$\hat{Y}_{mn} = -\frac{1}{Z_{12}} \quad (10)$$

Considering that all previous relations are complex equations, each parameter can be defined by its own module and shift. The module of Z_{12} represents the temperature oscillation amplitude on side n due to the periodic sinusoidal variation of the heat flux in the side m . The shift is the phase difference between the two sinusoid (temperature and heat flux). For a more detailed dissertation, authors invite to read the specific standard (ISO 13786).

Taking into account equation 3, the periodic thermal transmittance of the one-dimensional wall ($\hat{Y}_{1D}$) can be calculated by the standard, once the thermal properties of the material are retrieved.

From the definition of periodic thermal transmittance it is possible to evaluate the periodic thermal transmittance of the composite element ($\hat{Y}_{all}$) constituted by the one-dimensional wall and the singularity, knowing the temperature and heat flux oscillations. In order to perform this calculation, the model complexity makes not possible the use of the standard, but the analysis needs either experimental tests or numeric analyses to investigate the dynamic behaviour of this building element. In particular, if the definition of the heat transfer matrix for a multi-layer wall is sufficient for the definition of periodic thermal transmittance, for a 2D

domain the ratio of the equation 8 has to be calculated by means the creation of periodic oscillations in the boundary layer of the domain. The periodic oscillation of temperature can be created either in experimental setup or in a virtual environment for a numeric analysis. Thus, the effect of the singularity in a complex model can be defined applying the same concept of extra-flux above mentioned for the linear thermal transmittance.

The linear periodic thermal transmittance of the thermal bridge can be calculated with the following expression, considering L as the length of the thermal bridge:

$$\hat{\Psi}_{periodic} = \frac{\hat{Y}_{all} - \hat{Y}_{1D}}{L} \quad (11)$$

Model of the thermal bridge

The analysis has been performed on a particular model of thermal bridge, in order to study the same element both numerically and experimentally.

The present paper shows only the numeric analysis, that will be validated with experimental measurement in further analyses.

The studied thermal bridge is a stoneware tile inserted in two wood panels (Figure 2). The thickness of the model is equal to 10 mm, the dimensions of the panel are represented in the drawing. The geometry has been implemented in a 2D domain, considering its depth equal to 1 meter.

Figure 2: Model of thermal bridge (mm).

The thermal bridge is caused by the high difference between the thermophysical properties of the two materials (Table 1).

Table 1: Thermophysical properties of the materials constituting the thermal bridge.

Material	Thermal conductivity [W/mK]	Density [kg/m ³]	Specific heat [J/kgK]
Wood	0.1	721	3,000
Stoneware tile	1.4	2,200	700

Using a numerical software (ANSYS Fluent) for the analysis, the model has been divided with structured mesh of 0.5 mm of sizing (Figure 3).

Figure 3: Particular of structured mesh of the model.

In order to create the conditions of the standard, a sinusoidal function with a 5 K amplitude and a period of 86,400 seconds (mean value 273 K) has been applied to one side, while a constant value of 293 K has been fixed for the other side. During the simulation, the surface temperature and the heat flux values have been retrieved each 60 seconds.

Results

The one-dimensional walls in the chosen thermal bridge are the wood panel and the stoneware tile. The thermal bridge becomes tangible by the extra-flux due to the coupling between these two different materials. From the thermal and geometric properties of the model, the periodic thermal transmittances can be calculated with the standard ISO 13786 (Table 2):

Table 2: Dynamic properties of the homogenous walls.

Material	Symbol	Periodic thermal transmittance semi-amplitude (W/m ² K)	Periodic thermal transmittance time shift (sec)
Wood	$\hat{Y}_{wood}$	3.365	-1,430
Stoneware tile	$\hat{Y}_{stoneware}$	4.920	-802

Considering the entire model (stoneware tile and wood panel), with the results of the 2D simulation, the imposed oscillation of the temperature on side 1 creates an oscillation of the flux on side 2. In figure 4 is shown the correlation between the temperature and heat flux oscillations on the opposite sides of the thermal bridge model.

The heat flux can be expressed by its semi-amplitude, that it is equal to 18.23 W/m² and the time shift, which is in turn equal to -22,740 seconds.

From the definition of thermal transmittance, according to equation 8, dividing the complex heat flux by the complex temperature, the periodic thermal transmittance can be evaluated (Table 3).

Table 3: Dynamic properties retrieved by the 2D simulation (homogeneous wall + thermal bridge).

Material	Symbol	Periodic thermal transmittance semi-amplitude (W/m ² K)	Periodic thermal transmittance time shift (sec)
2D model (wood + stoneware tile)	$\hat{Y}_{2D}$	3.646	-1,140

Considering the specific surface of the different materials, according to the equation 11, the linear periodic thermal transmittance of thermal bridge is equal to:

$$\hat{\Phi}_{periodic} = \frac{\hat{Y}_{2D}A_{2D} - \hat{Y}_{wood}A_{wood} - \hat{Y}_{stoneware}A_{stoneware}}{L} \quad (12)$$

Where A_{wood} is equal to 1.28 m² and $A_{stoneware}$ is equal to 0.2 m² and A_{2D} is their sum. The periodic linear thermal transmittance is equal to 0.125 W/mK, with a time shift of -79,827 seconds.

The effect of thermal bridge can be evaluated taking into account the heat fluxes that flow through the model. Figure 5 shows the comparison between the heat flux considering only two one-dimensional panels, calculated with the standard (ISO 13786), and the heat flux retrieved by the simulation of the entire model.

It is interesting to notice in the plot the effect of the thermal bridge acts not only on the semi-amplitude but on the time shift as well. The presence of thermal bridge increases the maximum value of the sinusoid of around 0.5 Watt and the wave shift of around 3 minutes.

Figure 4: Temperature oscillation on side 1 and correlated heat flux oscillation on side 2.

Figure 5: Comparison between the heat flux flowing through the model with or without thermal bridge.

Conclusion

Thermal bridges are the weak points of the envelope in terms of heat losses. The research about this topic is not really developed, especially regarding the dynamic behaviour of this structure. The linear thermal transmittance is the main parameter that describes a thermal bridge in the steady-state regime. For the homogeneous wall, the standard EN 13786 gives a guide to perform calculation in order to retrieve the periodic thermal transmittance. Matching together the concept of linear thermal transmittance and the theory of periodic thermal transmittance for the homogeneous standard is the principal result of this paper. The definition of linear periodic thermal transmittance provides a quantitative approach for the dynamic characterization of the thermal

bridge. Before performing experimental validation, a methodology applied on a particular thermal bridge using a CFD approach has been proposed. In a panel composed by wood and stoneware tile the dynamic effect of the thermal bridge between the two materials was calculated, firstly characterizing the two materials with the standard EN13786, then implementing the geometry in a 2D simulation software to obtain information on the extra-flux existing from the matching between the materials. Thus, the linear periodic thermal transmittance of the thermal bridge has been defined. The future works will have the aim to validate this methodology that could be a useful instrument to create several types of thermal bridge structures in order to define a new standard with atlas of linear periodic thermal transmittances.

References

- Aguilar, F., Solano, J.P. and Vicente, P.G. (2014) Transient modeling of high-inertial thermal bridges in buildings using the equivalent thermal wall method. *Applied Thermal Engineering* 67(1–2), 370–377.
- Ascione, F., Bianco, N., De Masi, R. F., Mauro, G. M., Musto, M. and Vanoli, G.P. (2014) Experimental validation of a numerical code by thin film heat flux sensors for the resolution of thermal bridges in dynamic conditions. *Applied Energy* 124, 213–222.
- Gao, Y., Roux, J. J., Zhao, L. H. and Jiang, Y. (2008). Dynamical building simulation: A low order model for thermal bridges losses. *Energy and Buildings* 40(12), 2236–2243.
- International Organisation for Standardisation (2017). *Thermal bridges in building construction -- Heat flows and surface temperatures -- Detailed calculations (ISO 10211)*.
- International Organisation for Standardisation (2017). *Thermal bridges in building construction -- Linear thermal transmittance -- Simplified methods and default values (ISO 14683)*.
- International Organisation for Standardisation (2017). *Thermal performance of building components -- Dynamic thermal characteristics -- Calculation methods (ISO 13786)*.
- Mao, G., and Johannesson, G. (1997) Dynamic calculation of thermal bridges. *Energy and Buildings* 26(3), 233–240.
- Martin, K., Campos-Celador, A., Escudero, C., Gómez, I. and Sala, J.M. (2012) Analysis of a thermal bridge in a guarded hot box testing facility, *Energy and Buildings* 50, 139–149.
- Martin, K., Erkoreka, A., Flores, I., Odriozola, M., and Sala, J. M. (2011) Problems in the calculation of thermal bridges in dynamic conditions *Energy and Buildings* 43(2–3), 529–535.
- Martin, K., Escudero, C., Erkoreka, A., Flores, I. and Sala, J.M. (2012) Equivalent wall method for dynamic characterisation of thermal bridges. *Energy and Buildings* 55, 704–714.
- Tadeu, A., Simões, I., Simões, N. and Prata, J. (2011) Simulation of dynamic linear thermal bridges using a boundary element method model in the frequency domain. *Energy and Buildings* 43(12), 3685–3695.
- Viot, H., Sempey, A., Pauly, M. and Mora, L. (2015) Comparison of different methods for calculating thermal bridges: Application to wood-frame buildings. *Building and Environment* 93, 339–348.