Dynamic Characterization of Thermal Bridges in Historic Balconies in Palermo

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Abstract

The improvement of the energy performance of a historic building entails a process of intervention that should take into account the historical, aesthetic, technical and material features. The first step of the retrofit process is an accurate knowledge of the thermal behaviour of historic building in order to preserve this heritage and reduce their impact on the environment. In terms of the thermal characterization of the construction elements of the traditional building in the Mediterranean region, the balconies constitute a disruptive element of the heat transfer by the envelope. Although there are many catalogues that collect typical actual constructive solutions with the corresponding thermal bridge values, the use of catalogues induces an error of 35% compared to physical reality. In this paper, we present a numerical method for the evaluation that takes into account the effects of thermal mass of thermal bridges in different historic balconies in the city of Palermo. We select typical construction details of balconies based on relevant literature on traditional architecture in Palermo. We present internal heat flow results and we compare them with the results of homogeneous envelope. Finally, we relate the results performed in dynamic and steady conditions.

1. Introduction

The improvement of the energy performance of a historic building entails a process of intervention that should take into account the historical, aesthetic, technical and material features (Genova, 2016).
The first step of the retrofit process is an accurate knowledge of the thermal behaviour of historic buildings in order to preserve this heritage and reduce its impact on the environment. In the last few decades, the need to reduce energy consumption in the construction have led to finer analyses of the energy demand of buildings, taking into account time-varying parameters (Martin et al., 2011).
One of the first targets is therefore the reduction of energy losses by the envelope (Martin et al., 2012). Energy simulation software for buildings (BES) is providing an increasing number of results close to real energy demand with the implementation of dynamic analysis taking into account realistic conditions (Martin et al., 2011).
In terms of the thermal characterization of the construction elements of the traditional building in the Mediterranean region, the balconies constitute a disruptive element of the heat transfer by the envelope. In other words, they constitute thermal bridges (TB). Thermal bridges have a significant weight in the energy balance of a building (Citterio et al., 2008; Erhorn-Kluttig et al., 2009; Theodosiou et al., 2008).
A thermal bridge is a disruptive element of the heat transfer by the envelope, an area with more losses than the rest of the envelope. There might be two main causes for thermal bridge: one related to the geometry of the constructive node (presence of corners) and the other related to changes in materials or thermal resistances.
The need to facilitate the calculation of the effect of thermal bridges, simplified steady-state calculation methods have been developed in directives of different countries (Martin et al., 2011).
According to EN ISO 14683 (ISO 14683, 1999), there are different ways to calculate the TB heat transfer (Martin et al., 2012):

- Using the catalogues that collect the main technological solutions;
- Using a manual calculation for thermal bridges;
- Using a finite element method or a finite difference method.

Part of
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In this paper, we present a dynamic finite element method taking into account the effects of thermal mass of TB for the evaluation of different kinds of historic balconies in the city of Palermo. We present results and we compare them with those of homogeneous envelope. Finally, we relate the results in two different types of balcony calculated in dynamic and steady conditions.

2. Method and Simulations

2.1 Method

In order to define the simulation, we consider a general transient thermal problem, on a domain Ω, governed by the equation of heat and Fourier's law:

$$\begin{cases} \rho c_p \frac{\partial T}{\partial t} + \mathrm{div}\ (\underline{q}) = f \\ \underline{q} = -\lambda\ \underline{\mathrm{grad}}(T) \end{cases} \qquad (1)$$

T is the temperature;
q is heat flow;
t is the time;
f is the calorific heat capacity generated by a heat source;
ρ is the density;
c_p is heat capacity at constant pressure;
λ is thermal conductivity.

The equation system (1) is complete with the initial state and the boundary conditions.

- Initial state;
- Imposed heat flow condition (adiabatic conditions in cut-off planes);
- Convective boundary conditions.

For this last condition, we consider the convective heat transfer, on a surface $\partial\Omega_C$, according to Newton's law:

$$q = h\ (T_{ext} - T) \qquad (2)$$

T is the temperature on the convection surface $\partial\Omega_C$;
q is convective heat flux passing through the convection surface (positive if the heat flux is directed into the system);
h is the convective exchange coefficient;
T_{ext} is the outside temperature.

The spatial discretization of this system of equations on a mesh of finite elements can be reduced to the following system of equations, to solve with different time steps:

$$\underline{\underline{C}} + \dot{\underline{T}} + \left(\underline{\underline{K}} + \underline{\underline{H}}\right)\underline{T} = \underline{Q} + \underline{Q_C} \qquad (3)$$

$\underline{T}$ is temperatures at the nodes;
$\dot{\underline{T}}$ is the time derivative of the temperatures at the nodes;
$\underline{Q}$ is the heat flux integrated into the nodes;
$\underline{\underline{C}}$ is the capacity matrix;
$\underline{\underline{K}}$ is the conductivity matrix;
$\underline{\underline{H}}$ is the convection matrix;
$\underline{Q_C}$ is the term representing hTe.

2.2 Simulation in Steady-State

In steady state, an algorithm using the finite elements method is developed on Cast3m to solve Equation 3.
The boundary conditions are:

- a temperature difference of 20 K between inner and outer environments;
- a surface resistance equal to 0.13 m^2K/W for inside and to 0.04 m^2K/W for outside (according with ISO 6946).

2.3 Simulation in Dynamic State

In dynamic conditions, the external environmental parameters are characterized by significant variations over a period of 24 hours. To take into account these oscillations, the external temperature variations can be represented by a sinusoidal curve. According to Fig. 1, for a typical summer day in Palermo with a variation of +/- 15 K is used for the calculation.
Finally, we define heat flow conditions as a load that specifies the evolution of the convection outside temperature over time.

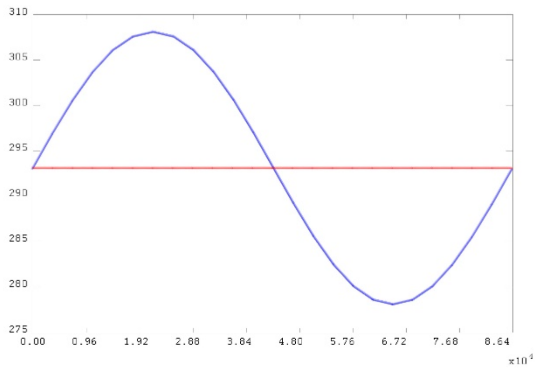

Fig. 1 – External temperature (blue curve) for a summer day and internal temperature (red curve)

2.4 Case Studies

In the Mediterranean region, climate and lifestyle have always favoured the construction of balconies, not only to provide enjoyment of the sun or protection from it, but also to have a direct relationship between the interior of the house and the street (Fatta, 2002). In spite of the differences in executive and formal qualities, there are two main types of balconies in Palermo: the first with stone consoles, which penetrate completely into the masonry. The second type is made of steel bars (Fig. 2).

Turning to the constructive solutions that will be compared, we consider two types of balconies, the first with a metallic I-beam and low thermal inertia and the other with *calcarenite* stone and high thermal inertia. We analyse the geometry, compositions and materials of these constructive solutions (Fatta, 2002). The thermal properties listed in Table 1, which define the constructive solutions of Fig. 3 are based on relevant literature on traditional architecture in Palermo (Genova, 2016).

Fig. 2 – The main types of balconies. Stone balcony (on the top), metallic balcony (on the bottom) (picture by Zarcone Roberta, 2017)

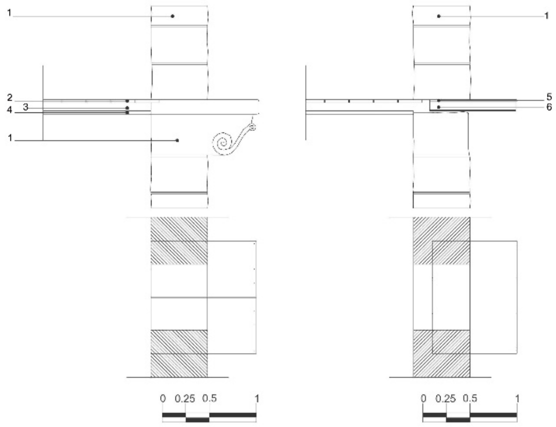

Fig. 3 – Setting up of: stone console (on the left) and metallic console (on the right)

Table 1 – Thermal properties of balcony constructive solution

Material	**ρ** $[kg/m^3]$	**λ** $[W/mK]$	c_p $[J/kgK]$
1. *Calcarenite* stone	1600	0.75	800
2. Floor tile	880	0.7	800
3. Mortar	1700	0.5	1000
4. Wood board	500	0.2	1600
5. Marble	2700	0.3	840
6. Metallic beam	27000	30	350

2.5 Results and Discussion

First, we compare the results of internal heat flow for each type of balcony with the homogeneous wall (HW) in dynamic state.

By plotting the results, we can note a difference between the heat flow in TB and in the HW (Fig. 4). For the balcony with metal console, as expected, the heat flow and the phase lag through the node are greater than on the homogeneous envelope. This is not always true for the balcony with a stone console. Indeed, the presence of the stone console increases the thickness and therefore the thermal inertia of the node; the effects of thermal bridge are reduced, due to the presence of a greater thickness of the stone. Table 2 shows numerical values of amplitude (absolute difference between the maximum or minimum interior heat flow from the average thermal flow) and phase lag (time that the outer thermal wave takes to penetrate inside the enclosure). Comparing these results, it is possible to notice how the presence of the metal console reduces the phase lag compared to the homogeneous envelope by almost 5 hours. By comparison, the balcony with the stone console has a phase lag similar to that of the homogeneous envelope.

Secondly, we consider the internal heat flow in TB with standard methods, defined in steady state with an imposed temperature difference of 20 K, according with EN ISO 10211-2 (ISO 10211-2, 2007) (Fig. 5). We can note that the heat flux in the metallic balcony calculated in steady state is 1.5, higher than the stone one (Table 3). In dynamic conditions, the maximum heat flow is about 5.5 higher in the stone balcony than the metal one (Table 4). These results confirm that in the steady-state calculation, the assumptions made on the boundary conditions significantly affect the heat flow results. Not taking into account the temperature variation in time and therefore the thermal inertia of the nodes, the thermal flow gap in the two balconies is indeed considerably reduced compared to the real difference in thermal performance calculated in dynamic conditions.

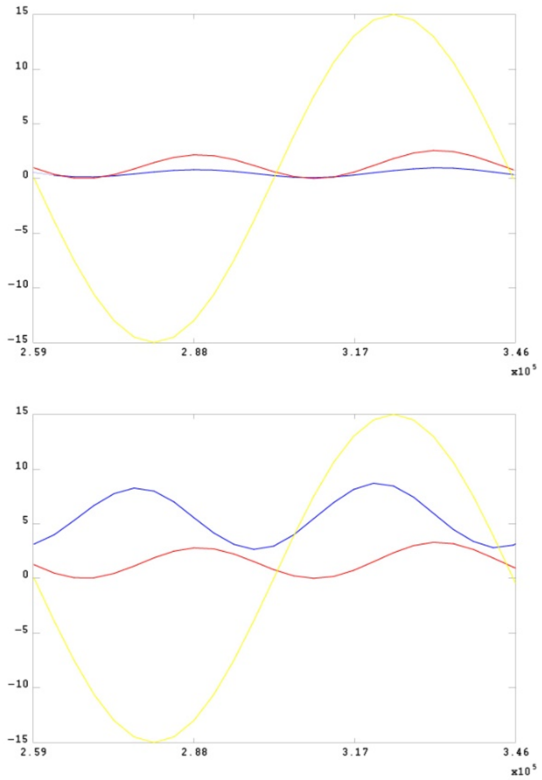

Fig. 4 – Comparison between heat flow on the node (blue curve), heat flow on the homogeneous part of the envelope (red curve) and temperature difference (yellow curve). Stone console (top) and metallic console (bottom)

Table 2 – Model's comparison of Qin amplitude and phase lag in homogeneous wall

Constructive solutions	A $\left[\frac{W}{m^2}\right]$	$\varphi\ [h]$
1. Stone balcony	0.34	15.33
2. Metallic balcony	1.54	10.75
3. Homogeneous wall	1.25	15.55

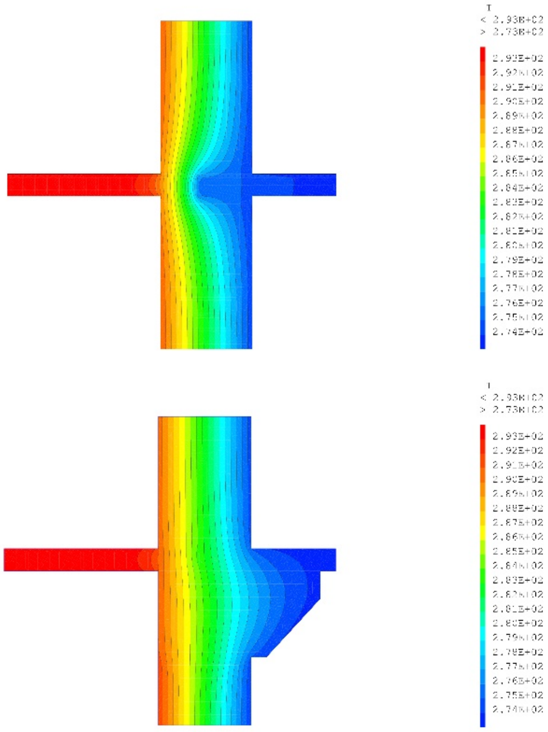

Fig. 5 – Temperature profile according to EN ISO 10211. Metal balcony (top), stone balcony (bottom)

Table 3 – Comparison between internal heat flow in steady model

Constructive solutions	$Q_{int}\left[\frac{W}{m^2}\right]$ Steady model
1. Stone balcony	11.04
2. Metallic balcony	16.11

Table 4 – Comparison between internal heat flow in dynamic model

Constructive solutions	$Q^{max}{}_{int}\left[\frac{W}{m^2}\right]$ Dynamic model
1. Stone balcony	1.57
2. Metallic balcony	8.96

3. Conclusion

In this paper, we presented the evaluation of thermal bridges on two typical traditional balconies in Palermo.

In the Mediterranean area, the use of stone in balconies leads to better thermal behaviours compared to metal balconies. In the case of the balcony with the stone console, we can disregard the influence of the presence of the balcony relative to a current part of the envelope. This means that with a calculation in steady state, it would be wrong to consider the balcony as a thermal bridge in the overall thermal balance of a building.

The dynamic calculations have shown that considering the inertia of the constructive component considerably reduces the effects of thermal bridge, by taking into account more correctly the real conditions.

The use of common catalogues can lead to 35% of errors, compared to physical reality. This error is due to different reasons: unreal dimensional and material characteristics of the node; calculation performed on steady state; boundary conditions not adapted to climatic area.

For an energetic intervention on the historic building, it seems necessary to conduct a phase of diagnosis of the constructive characteristics and its energetic behaviours with a fine approach of the thermal analysis.

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