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DYNAMIC BEHAVIOR OF THE BUILDING ENVELOPE: THEORETICAL PREDICTIONS AND EXPERIMENTAL ANALYSIS

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Summary: In the present paper the comparison between the results obtained from an extended series of numerical simulations on a composite wall and the experimental data collected in transient regime are presented. The experimental analysis is applied to a building of the University of Trento. The numerical simulations have been carried out using the standard EN ISO 13786 [1], the transfer functions method and also solving the heat equation by means of the discretization based on the finite element method.

Keywords: Keywords: Component dynamic behavior, CTF

1. INTRODUCTION

One of the aims of the EPB Directive 2002/91/CE is the increase of the buildings energy performances in summer.
Hence, the performances of the structures of the envelope have to meet not only the minimum law requirements on the thermal transmittance (relevant in winter), but also have to provide a suitable thermal response to the external heat fluxes, so that it is possible to decrease the thermal peaks and ensure an adequate internal comfort in summer.

It is known that the role of the opaque components of the envelope on the thermal balance of buildings depends both on their thermal resistance and capacitance that affects the heat transfer and energy storage process respectively. The former depends on the average value of the thermal gradients between the internal and the external environments, while the latter is strictly related to the time-dependent periodic component of the external heat load that involves the thermal capacitance of the envelope and, consequently, its thermal response.

The present work deals with the physical meaning of the conventional parameters that characterize the dynamic behavior of a building envelope component (wave phase displacement, decrement factor). This investigation is possible thanks to the comparison and validation against the experimental data of the results obtained by means of the standard procedures and by means of detailed (i.e. finite elements) methods.

2. METHODS

2.1. Simplified dynamic modeling

The European reference standard about the dynamic behavior of an external wall is the EN ISO 13786:2008 [1], but there are also different approaches based, for example, on transfer functions [2,3]. This standard rule simply characterizes the transient response of a building component by means of three parameters: the periodic transmittance, the decrement factor and the phase displacement of the heat wave.

The forcing term on the building component is described by the rule by means of a sinusoidal function of the temperature applied either on the internal or on the external side of the component, whose effects are the heat fluxes, also sinusoidal.

The heat flux is 1-dimensional, i.e. the thermal bridges are not considered in the calculations, the medium is assumed homogeneous. The standard rule defines the thermal admittance (1) and the periodic transmittance (2) as the ratio between the complex amplitude of the heat flux density through the component surface (adjacent the *m*-layer) and the complex amplitude of the temperature of the same layer (or the n-layer for the Y_{mn}), when the other layer temperature is quite constant. Thanks to (1) and (2) it is possible to compute the decrement factor (3).

$$Y_{mm} = \frac{\hat{q}_m}{\hat{\theta}_m} \quad (1)$$

$$Y_{mn} = -\frac{\hat{q}_m}{\hat{\theta}_n} \quad (2)$$

$$f = \frac{|Y_{mn}|}{U} \quad (3)$$

The standard rule defines the heat transfer matrix Z of a layer, that correlates the complex amplitudes of the temperature and heat flux on one side of the component with the same physical quantities on the other side (4).

$$Z = \begin{pmatrix} \hat{\theta}_2 \\ \hat{q}_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \cdot \begin{pmatrix} \hat{\theta}_1 \\ \hat{q}_1 \end{pmatrix} \quad (4)$$

with:

$$Z_{11} = Z_{22} = \cosh(\xi)\cos(\xi) + j \cdot \sinh(\xi)\sin(\xi)$$

$$Z_{12} = -\frac{\delta}{2\lambda}\left\{\begin{matrix} \sinh(\xi)\cos(\xi) + \cosh(\xi)\sin(\xi) + \\ j \cdot [\cosh(\xi)\sin(\xi) - \sinh(\xi)\cos(\xi)] \end{matrix}\right\}$$

$$Z_{21} = -\frac{\lambda}{\delta}\left\{\begin{matrix} \sinh(\xi)\cos(\xi) - \cosh(\xi)\sin(\xi) + \\ j \cdot [\cosh(\xi)\sin(\xi) + \sinh(\xi)\cos(\xi)] \end{matrix}\right\}$$

Since a building component usually consists of several layers, the whole transfer matrix is computed as the product of the single matrixes of each layer.

By means of this matrix it is possible to calculate the time delay (or wave phase displacement).

$$\Delta t_{ij} = \frac{T}{2\pi}\varphi_{ij} = \frac{T}{2\pi}\arg(Z_{ij}) \quad (5)$$

2.2. Experimental analysis

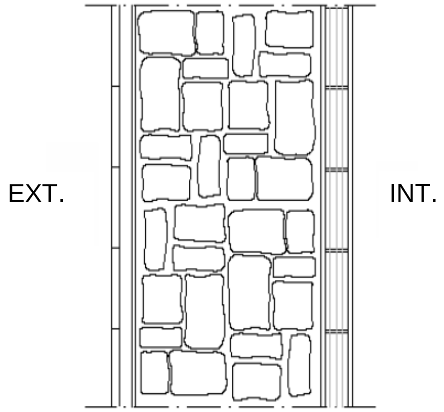
The experimental activity has been carried out in August 2008 at the Faculty of Engineering of the University of Trento. The chosen thermal zone is a room used for lectures which has two sides (north and west orientations) confining with the external environment. The campaign has been set up in order to measure the temperature and relative humidity of the air and the wall superficial temperature both for the internal and for the external sides.

The wall temperature has been monitored with contact thermistors (Econorma, FT-800/System) that use a stainless steel micro-recorder system similar to a coin, in shape and dimension (figure 1). The operation range is -40°C and + 85 °C, with a resolution of 0.5 °C according to EN ISO 7726:2001 [4]. Thermal conductive paste has been also applied in order to improve the thermal contact between the sensor and the wall.

The relative humidity and the temperature of the air have been measured by means of a capacity sensor equipped with a resistance thermometer Pt100 (Rotronic Hygro-Clip-S). This device operation characteristics are ±1 % U.R., ±0.3 K precision (in the range 23 ±5 °C), fast response time and anthracite envelope (figure 1).

Table 1. Opaque component: geometry and thermophysical properties

layer	**thickness** [cm]	**λ** [W/(mK)]	**c_p** [J/(kg K)]	**ρ** [kg/m^3]
INTERNAL				
plaster	1.5	0.70	837	1800
tile	8.0	0.40	934	700
plaster	1.5	0.70	837	1800
masonry	65.0	1.91	878	2300
plaster	1.5	0.90	837	1800
air	4.0	0.18	1004	1.204
granite	3.0	3.50	837	2600
EXTERNAL				



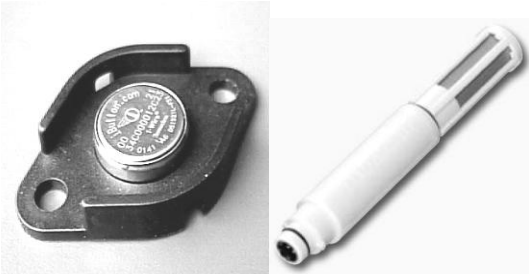


Fig. 1. Wall temperature sensor (on the left), temperature and relative humidity sensor (on the right)

For the present analysis it has been chosen the wall structure north-oriented. The wall is characterized by a total thickness of 84.5cm and by 7 different layer as showed by table 1, where the geometric and thermophysical properties have been also reported.

2.3. Complete modeling

The experimental measurements have been compared with the results of a dynamic thermal simulation of the system carried out through a finite element model.

The whole system has been discretized using a 2D (xy) geometry (in particular *x* coordinate refers to the wall width). The Partial Differential Equations (PDE's) discretization and solution procedure has been performed by means of the Comsol Multiphysics [5] commercial software. The temperature values - measured on the internal and external wall surface during the experimental activity - have been assumed as boundary conditions. These time-variable conditions on both sides of the wall allow to simulate the thermal behaviour inside the envelope structure with a high grade of reliability.

In a transient differential problem, characterized by a pseudo-periodic external forcing action, it is crucial to assume realistic initial conditions. The temperature distribution in the computational domain at the initial time step can be estimated using the stabilized periodic regime approach.

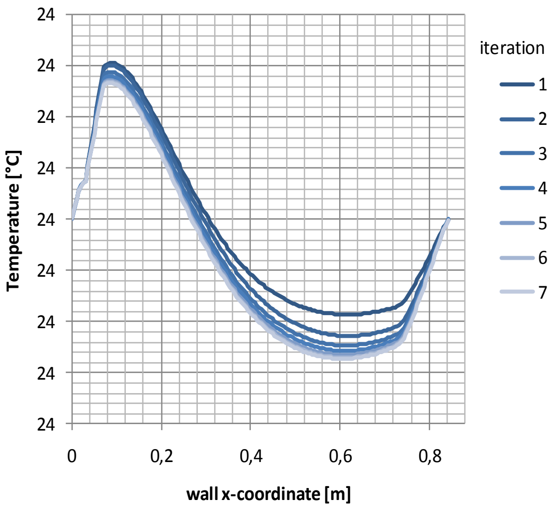
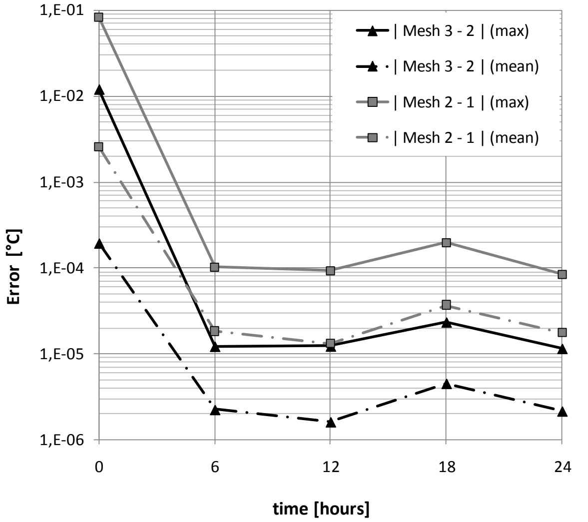


Fig. 2. Initial condition estimation: stabilized periodic regime approach.

For this purpose an iterative method has been applied, carrying out several simulations of the first day (figure 2). Every simulation takes as initial condition (hour 00.00) the thermal field obtained at the end of the previous simulation (hour 24.00). The procedure has been stopped when the maximum temperature difference between two consecutive iteration was 5×10^{-3} °C.

The discretization procedure has been subjected to a sensitivity analysis in order to assume a reasonable dimension of the computational mesh. Choosing a generic day of the month, 3 different simulations have been carried out increasing progressively the number of the elements (i.e., the degree of freedom, d.o.f.), that discretize the domain. Figure 3 shows the results of this procedure pointing out the error values computed comparing two different meshes.



Mesh: 1: 13122 d.o.f.; 2: 51943 d.o.f.; 3: 206685 d.o.f.

Fig. 3. Sensitivity analysis of the computational mesh

3. RESULTS AND DISCUSSION

3.1. Single-layer component

The results of this part of the work concerns the comparison between the values of the dynamic parameters (decrement factor and phase displacement) - of a single-layer wall subjected to a simple sinusoidal heat wave - both estimated by the EN ISO 13786 procedure and computed by means of the finite element approach. For this purpose a test case has been analyzed dealing with a homogeneous concrete wall of variable width. The comparison between the prediction of the standard rule and the f.e.m. simulation are reported in figure 4. For the f.e.m. simulation a convective boundary condition has been assumed for the internal side, keeping the air temperature to a constant value equal to the mean value of the external heat wave.

The comparison between the predicted and computed data shows a quite satisfying agreement for the displacement parameter, while the decrement factor is still under evaluation.

An increase of the wall width, and consequently, an increase of the thermal capacity of the component causes a corresponding increase of the phase displacement.

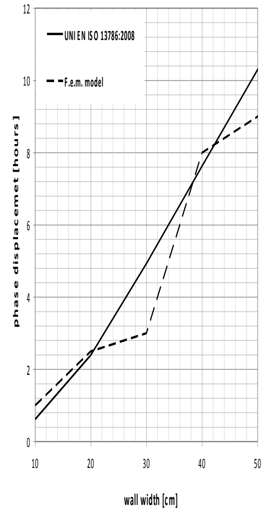


Fig. 4. Comparison between the prediction of the EN ISO 13786 and the f.e.m. simulation: phase displacement

3.2. Multi-layer component

A whole-month (August 2008) dynamic simulation has been carried out on the multi-layer opaque component by means of the finite element approach.

Figure 5 shows the computed results both in term of temperature variations at different position along the x-coordinate and in terms of heat flux on the internal and external wall surface (positive fluxes refer to the outside-inside direction).

Starting from the value computed by the f.e.m. model, the maximum, minimum and average temperatures have been calculated and plotted as a function of the x-coordinate, in order to give a local estimation of the damping factor of the building component (figure 6). On the basis of these values it is possible to observe that the amplitude of the heat wave decreases (as the damping factor decrease) along the x – coordinate until it reaches a minimum value (between 0.6-0.8 m). Then the damping factor slightly increases. This peculiar behavior is due to the major influence of the external forcing heat wave (decrease behavior) with respect to the low role of the internal load (slight increase behavior) induced by the system and by the internal sources.

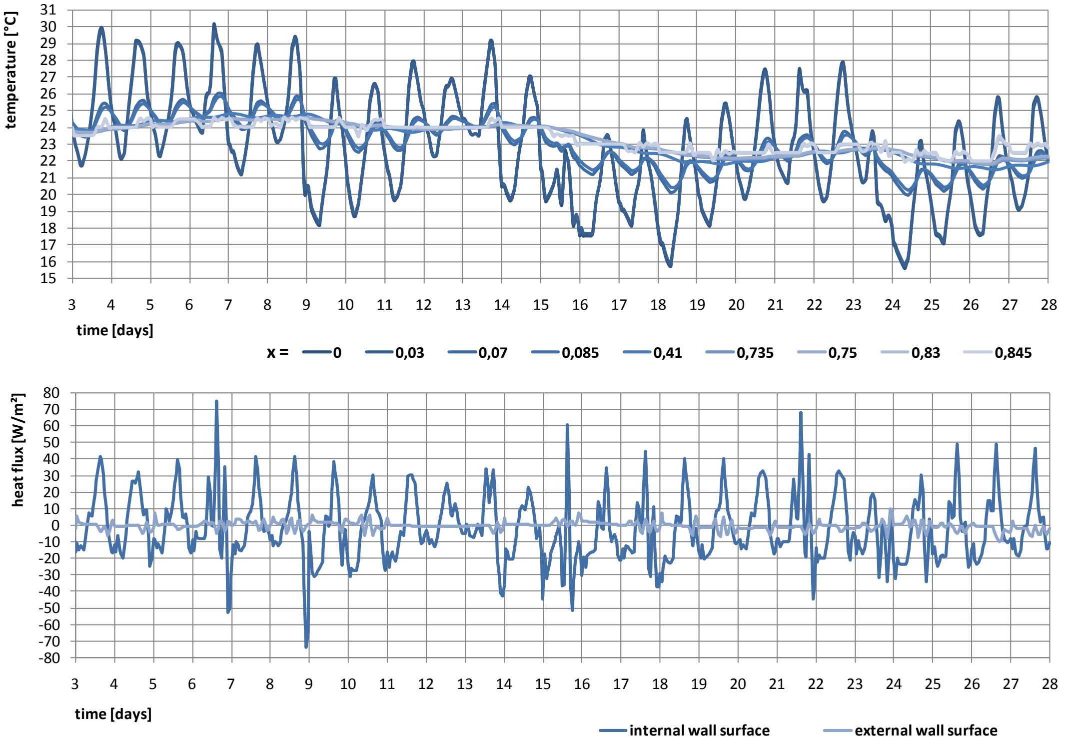


Fig. 5. Whole-month (August 2008) dynamic simulation results: temperature variations along the x-coordinate (above); heat flux variation on the internal and external wall surface (below)

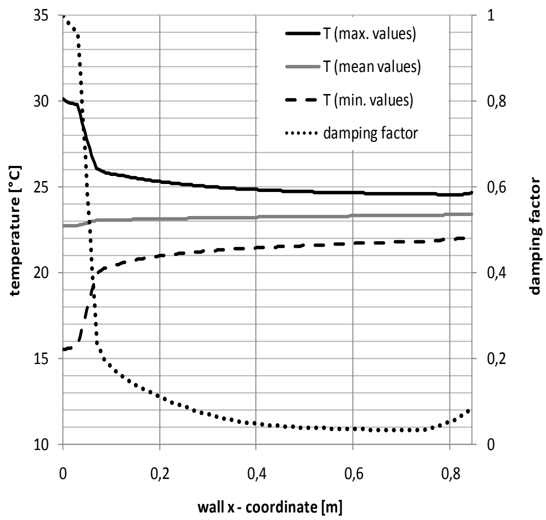


Fig. 6. Damping factor characterization

The estimation of a representative damping parameter for the wall is then not trivial, as the external forcing wave influences the wall up to a so called ′penetration depth′ (i.e., where the damping factor begins to increase). As a first guess, it is possible to characterize the damping factor by its minimum value (0.032). Another chance is to assume a semi-infinite medium behavior for the wall, interpolating the last significant layer (stone) by an exponential function (6) of the x-coordinate.

$$A \cdot \exp(\beta \cdot x) \tag{6}$$

Once estimated A and β the by the least squares method, it is possible to calculate the damping parameter at the inside boundary (internal surface) assuming a negligible contribution of the plaster. This second procedure give an estimate of 0.014 for the damping factor (0.17 and 2.91 for A and β respectively).

Moreover, an estimation of a decrement factor (as defined by the EN ISO 13786) from the f.e.m. simulation seems not meaningful, because of the influence of the internal load that induces a change in the sign of the heat flux of the internal side of the wall.

The computed data have been also used for a similar calculation procedure, in order to characterize the wall phase displacement. In this case the displacement of the heat wave phase has been estimated from the simulations results obtained for every interface between different layers. The displacement parameter is characterized by a quite linear variation along the wall width (figure 7).

By means of a linear regression (on the mean values) the representative phase displacement for the building component has been assessed at 21 hours at the internal wall surface (x = 0.85 m).

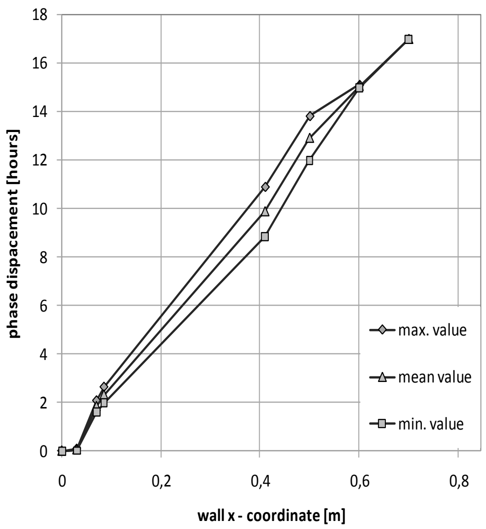


Fig. 7. Phase displacement characterization

The comparison of the results obtained by means of the complete modelling have been also compared with the prediction of the EN ISO 13786, obtaining a satisfying agreement (table 2).

Table 2. Complete modelling (f.e.m.) vs EN ISO 13786

	EN ISO 13786	**f.e.m. simulation**
Phase displacement	20.6	21.0

3.3. Conclusions

In the present paper the thermal dynamic response of an envelope building component has been analyzed through the comparison of the results obtained by means of both standard procedures and f.e.m. simulations against experimental data.

The physical meaning of the conventional dynamic parameters (wave phase displacement and decrement factor) of a single- and multi- layer wall has been also investigated.

The results point out a quite good agreement between the standard procedure and the detailed simulation for the wave phase displacement both for the single- and for the multi- layer wall.

For the multi-layer wall it is not trivial the estimation of a representative decrement factor from the f.e.m. simulation (based on the experimental data) in order to obtain a reliable comparison with the EN ISO 13786 results. This is mainly caused by the influence of the internal boundary condition (i.e., internal load), that causes a change in time of the sign of the heat flux on the internal side of the wall.

Furthermore, it has been proposed a method for the estimation of the wall penetration depth (arising from the damping factor calculation) and for the characterization of the phase displacement, based on the time-dependent distribution of the temperature along the wall width.

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