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Assessment of equivalent thermal properties of multilayer building walls coupling simulations and experimental measurements

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ABSTRACT

The growing effort of reducing energy needs in the building sector calls for an accurate characterization of the performances of external walls, which are the main cause of thermal exchanges and consequently are fundamental to realize accurate simulation models to evaluate and control thermal loads.

The dynamic characterization of a multilayer wall can be performed by defining its stratigraphy and the thermo-physical parameters of each layer. When existing buildings are investigated, technical specifications may be unknown or difficult to obtain due to documents lost over time; furthermore, aging may have altered the building materials characteristics. In these cases, in-situ measurements become essential but there is the need to analyze the behavior of walls considering their dynamic characteristics, not obtainable by employing non-destructive tests, such as the heat-flow meter method.

The paper aims to verify if an equivalent homogeneous wall can be associated to a multilayer wall in the sense of producing the same behavior if exposed to the same outdoor environmental conditions. Findings in literature demonstrate that, generally, this is not exactly achievable. However, the possibility of an approximate equivalence is investigated in this work by means of finite-element simulations and experimental measurements. The results obtained in actual case studies show that this equivalence can be made, obtaining preliminary satisfying results. The proposed methodology can be employed in existing and historical buildings to achieve useful equivalent data directly applicable for the energy retrofit phase and for achieving a better coupling between the building and the heating/cooling system, reducing environmental impacts.

1. Introduction

In recent years, the scientific community demonstrated a very large interest in building energy performance and energy saving issues [1–3] due to the fast depletion of conventional energy sources and increasing environmental pollution. This criticism has grown very fast in recent years as much to make the reduction of fossil fuels consumption and pollutant emissions a government's critical issue. Building energy performances need to be improved by means of measures that take into account climatic and local conditions as well as the characteristics of the built environment. It is well-known that ancient countries, such as Italy, are characterized by a large historical heritage which, due to law constraints, needs specific retrofit procedures [4]. In situ measurements are fundamental to investigate this category of buildings but, at the same time, destructive tests cannot be performed. On the other hand, old buildings are composed of massive elements, characterized by a high thermal inertia. For these reasons, it is important to assess the dynamic behavior of these buildings, creating accurate energy consumption models.

Energy performance of buildings is usually evaluated by means of software simulations and many findings in literature [5–8] show the widespread use of calculation codes to model and design buildings behavior. While the degree of accuracy of the physical model may vary between the different software implementations, in any case the description of the thermal behavior of a building requires the input of technical information such as structural geometry, walls thermal resistance, intended uses, geographical location, occupation's scheduling and heating and cooling systems information [9,10].

When new constructions are addressed, a complete set of information is usually available, thanks to the design phase; materials thermo-physical properties are generally taken from products data sheets. On the contrary, when existing buildings are investigated, technical specifications may be unknown or difficult to obtain because many documents can be lost or structural/aging variations may have altered the building composition. In such cases, on-site measurements become essential [9–11]. It is possible to carry out different tests on buildings

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Nomenclature

c	Specific heat capacity [J/kgK]
$\overline{m}$	Average measured value
m_i	Measured value at time t_i
N	Total instances data set
q	Heat flux [W/m^2]
s_i	Simulated value at time t_i
t	Time [s]
T	Temperature [°C]
T_{ext}	External air temperature [°C]
T_{int}	Internal air temperature [°C]
T_{se}	External surface temperature [°C]
T_{si}	Internal surface temperature [°C]
U-value	Thermal transmittance [W/m^{2}K]
λ	Thermal conductivity [W/mK]
λ_{eq}	Equivalent thermal conductivity [W/mK]
ρ	Mass density [kg/m^3]
CV(RMSE)	Coefficient of variation of Root Mean Square Error
EF	Model efficiency
MBE	Mean Bias Error

masonries whose distinction is based on their destructiveness degree [12]. Destructive tests require the removal of structure samples by using core-drills, altering the wall; these tests include techniques such as endoscopy and wall drilling. Non-destructive tests do not need the wall destruction or removal of structure samples; these tests include thermography, heat flow meter measurements, environmental monitoring and blower door test. Non-destructive tests are based on surface temperature probes, heat-flow sensors and on the detection of infrared radiated heat.

Infrared thermography is a useful technique for obtaining qualitative results about thermal losses through the building envelope [13,14], about heating and cooling systems failures or to identify electric cables or pipes paths. On the other hand, heat flow meters are appropriate instruments to measure the thermal transmittance (U-value) of existing buildings envelopes when the composition layers of the walls are unknown. However, the conventional post-processing of the measured data allows to obtain information about the wall behavior under a steady state regime [15,16]. The dynamic characterization of a wall can be achieved by specifying its overall thermal resistance together with parameters that take into account inertial effects. While the thermal resistance is simply determined by imposing or extrapolating to steady-state conditions, the second property of the wall is not quantified by a single parameter and several approaches have been proposed in scientific literature to evaluate it. In any case, the determination of thermo-physical properties is an example of parameter estimation as an inverse heat transfer problem [17], a subject that has been addressed by several authors in the context of building applications [18].

Antonopoulos et al. [19] presented an analytical method for in situ assessment of the thermal properties of a wall made of different layers and they validated it by comparing theoretical and experimental data, finding an agreement with the a priori known values. Simoes et al. [20] presented an experimental validation of a semi-analytical model for dynamic heat transfer in systems characterized by multiple layers, achieving a reliable method for studying transient 1D and 3D heat conduction. Moreover, in their study, Tadeu et al. [21] proposed and validated an iterative dynamic model to assess thermal resistance of a wall, based on the Newton–Raphson method, where the external heat fluxes and temperatures are defined.

Chaffar et al. [22], with the aim of determining the thermo-physical parameters of a homogeneous layer, employed together thermal stresses combined with infrared thermography measurements, using a specific experimental set-up. An iterative minimization algorithm was used in order to achieve the error minimization between the simulated temperatures (provided by using reference values) and the experimental ones, recorded by the infrared camera. Faye et al. [23] presented a method to estimate the effective heat capacity of a symmetric wall made of heterogeneous materials. An analytical model based on the thermal quadrupole method was developed and it was validated experimentally by employing a climatic chamber, under sinusoidal boundary conditions. Other authors, such as Orosa and Oliveira [24], used the time constant to characterize the thermal inertia of a wall. They analyzed the thermal inertia of two schools (characterized by different inertial behaviors) by simulating them and applying the linear regressions of the logarithmic temperature differences with respect to the outdoor conditions. Parameter estimation can also be performed by means of stochastic methods, which allow overcoming a few of the limitations of deterministic approaches, especially the multiple-minima nature of the function to be minimized [25,26].

One of the inconveniences with the parameter estimation approach is that, if the wall internal structure is unknown, also the number of parameters to be determined is unknown. Therefore, it could be useful to represent the wall by an approximate homogeneous equivalent wall. In literature, the possibility to obtain a homogenous medium that is equivalent to a two-layer slab exposed to a thermal flux that is uniformly distributed on one face was analyzed [27]. The authors investigated if characteristic conductivity and volumetric heat capacity of the homogenous material equivalent to the two-layer slab can be determined. By using the quadrupole matrix approach, they concluded that there is no homogenous medium that can be equivalent to a two-layer slab, except in the particular case where the two layers thermal effusivities are the same [27].

Beyond this fundamental limitation, one can ask if an approximate equivalence is however possible and to what extent an equivalent wall made of a single homogeneous material can reproduce the dynamic thermal behavior of different multilayer walls. This is the subject of the present work, where the possibility of an equivalent homogeneous wall to be associated to a multilayer wall, in the sense of producing approximately the same effect to thermal solicitations, is investigated. This is done by generating the equivalent models of actual multilayer walls, using both a simulation software and in situ measurements. Clearly, the parameter estimation of the resulting homogeneous wall turns out to be a much simpler problem than the original one. The possibility of describing multilayer walls by means of equivalent ones and the prospect to find equivalent thermal properties could overcome the lack of essential technical information for existing buildings, in order to define the dynamic characterization of walls. It is noticeable that the proposed approach can be essential in the retrofit phase of existing buildings and historical ones, due to the architectural constraints that characterize almost all the Italian historical heritage.

The paper structure is as follows. In Section 2, we deal with the aim and scope of the research, focusing on the novelty of our work. In Section 3, we describe in detail methodology, materials and experimental setup. In Section 4, we describe, compare and discuss the simulated and experimental results. In Section 5, we draw the conclusions.

2. Aim and scope of the research

The complexity of building construction and retrofit design phase is often addressed by resorting to an extensive use of simulation software. In these cases, it is possible to realize predictive models by means of dynamic software, employing information directly obtained from the product data sheets. On the other hand, when building renovations are considered (if there is no demolition of the envelope), aiming at