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Article

In Situ Thermal Transmittance Measurements for Investigating Differences between Wall Models and Actual Building Performance

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Abstract: An accurate assessment of a building's wall performance, defined through the thermal transmittance, is essential to compute the annual energy consumption. Analyzing opaque surfaces, the heat transfer across walls can be modeled by an electro-thermal analogy, based on resistors series, crossed by a one-dimensional heat flow. This analogy is well established and it refers to stratigraphy composed of homogeneous materials. When dealing with inhomogeneous materials, possibly including hollow bricks, the wall's thermal transmittance is evaluated by means of an effective conductance. However, in order to verify the theoretical models effectiveness, a comparison with *in situ* measurements is needed. In this paper, three building walls characterized by different stratigraphy have been analyzed; by employing a heat flow meter investigation. Measurements results and estimated thermal transmittance values—calculated applying the standard UNI EN ISO 6946—have been compared.

Keywords: wall thermal transmittance; *in situ* measurements; heat-flow meter

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1. Introduction

It is well known that a building's components' characteristics influence annual energy consumption [1–10]. Wall performances depend on the thermal conductivity of each layer constituting the wall, which gives information about how heat flows through a structure, and on the heat capacity of the layers, which is related to material heat storage. When information about materials thermal properties is not available, the thermal conductivity and conductance values can be found in the UNI standards for typical building envelopes [11,12]. Higher thermal resistance values are obtained with lower thermal conductivity values. Overall performance depends on material type, thickness and mass density of each layer. In a steady state, the one-dimensional heat transfer across walls can be modeled, with an electrical analogy, as heat current flowing through thermal resistors. This electro-thermal analogy is well known and it is used to calculate heat transfer when wall thermal properties are known or *vice versa*. Frequently, however, the actual thermal resistance of building components may be different from the value estimated during the design phase. Therefore, it is important to investigate the building envelope through specific measurements [13,14]. Currently, there are two common measurement techniques to evaluate the thermal resistance in existing buildings: direct measurement of the heat-flux (non-destructive method) [15,16], or direct survey of the fabric layers with direct measure of their thickness (destructive method) [17]. The non-destructive method requires the use of a heat flow meter that has to be operated according to the standard ISO 9869 [18]. A comparison between different measuring methods of buildings envelope thermal resistance was performed by Desogus *et al.* [19], who applied invasive and non-invasive methods to measure the thermophysical characteristics of a test wall, using the heat-flux meter technique and the destructive sampling method. Thermal resistance measurements could be wrong if structural abnormalities are found in the measuring points. For this reason, a preliminary thermographic analysis is required. Asdrubali *et al.* [20] presented the results of a thermal transmittance measurement campaign, performed in some green buildings. The differences between calculated and measured values ranged from −14% to +43%. The analyzed walls were previously monitored with thermographic surveys in order to assess the correct application of the sensors. The thermographic tool proves very useful to investigate building's characteristics and its vulnerability. As an example, De Lieto Vollaro *et al.* [21] used a thermal imaging camera to analyze the envelope of an old building, highlighting the presence of some badly covered holes (probably old windows). The instrumental diagnosis is an essential step to investigate the building's envelope and build a model able to represent the real structure thermal behavior.

In this contribution, the results of *in situ* thermal transmittance measurements conducted on the walls of different buildings located in Italy are presented. A comparison between the values calculated through the electro-thermal analogy, employing the thermal conductivity and conductance values specified by the standards, and the measured data, obtained by performing a heat-flow meter measurement campaign, has been carried out. Our aim, in particular, was to focus on such situations were destructive testing is not possible and one has to rely only on *in situ* measured temperature data to estimate thermal transmittance.

2. Methods for Thermal Transmittance Calculation and Measurement

The UNI EN ISO 6946 [22] describes a method for calculating the thermal resistance and thermal transmittance of building elements based on the electrical analogy. References to thermophysical properties of some representative materials are provided in this standard [11,12] and the wall thermal resistance is accordingly calculated using the series thermal resistance of the single layers:

$$R_i = \frac{d_i}{\lambda_i} \tag{1}$$

$$R_{tot} = R_{si} + \sum_i R_i + R_{se} \tag{2}$$

$$U = \frac{1}{R_{tot}} \tag{3}$$

where d_i is the thickness of the i-th layer, λ_i is its thermal conductivity, R_{tot} is the total wall thermal resistance including the internal and external surface resistances R_{si} and R_{se}, U is the thermal transmittance. The surface resistances are defined as follows:

$$R_s = \frac{1}{h_{conv} + h_{irr}} \tag{4}$$

$$h_{irr} = 4\varepsilon\sigma T_m^3 \tag{5}$$

where h_{conv} is the convective coefficient which depends on air velocity, h_{irr} is the radiative coefficient, ε is the surface emissivity, σ is the Stefan-Boltzmann constant and T_m is the average thermodynamic temperature between the one of the analyzed surface and the one of the surrounding surfaces.

When a heterogeneous layer is characterized also by air gaps, the standard introduces an equivalent thermal conductivity defined as:

$$\lambda^{II} = \frac{d_j}{R_g} \tag{6}$$

$$R_g = \frac{1}{h_a + 2E\sigma T_m^3 (1 + \sqrt{1 + d^2/b^2} - d/b)} \tag{7}$$

where h_a is the conductive/convective coefficient, E is the emittance between the surfaces that make up the cavity, d is the cavity thickness and b is the cavity width.

In the following, when taking into account inhomogeneous materials, both an effective thermal conductivity and the thermal conductance will be reported.

Methods based on dynamic analysis [23,24] are also frequently used to determine thermal transmittance based on temperature measurements. This approach has not been employed here since we were just concerned with the steady state thermal transmittance to be compared with the measured value provided by the heat flow meter.

In situ thermal transmittance measurements have been conducted to appreciate the effectiveness of the Standard procedure. Measurements have been carried out on the walls of three buildings belonging to three different historical periods: an old building, which dates back to the late 1800s, an early-1950s structure, and, finally, a house built 15 years ago (see Figure 1). First of all, as shown in Figure 1, site inspections have been conducted, in order to assess the wall's stratigraphy and to reproduce a model to employ for the calculation of the thermal transmittance. The old building and the house visual inspections have been done during the property renovations. The wall characteristics of the early-1950s building have been deduced through visual inspections of the bins containing the shutters, as shown in Figure 2b. Figure 2 shows only two buildings during the retrofit stage because the third case study has been already renovated. Despite this the stratigraphy information is known.

(**a**) (**b**) (**c**)

Figure 1. External views of the analyzed buildings. (**a**) The old building; (**b**) the early-1950s building; (**c**) the 2000s house.

(**a**) (**b**)

Figure 2. Visual inspection of the old building envelope (**a**) and of the early 1950s structure envelope (**b**).

Thermal transmittance values have been measured by using the heat flow meter [25]. The instrument is provided with two temperature sensors: a plate that has to be applied on the inner side of the wall and an external wireless temperature probe. Measurements of *in situ* thermal transmittance have to be performed in agreement with the Standard ISO 9869: accordingly, measurement has been carried on for at least 72 h, with an acquisition time step equal to 5 min. The measurements have been conducted during winter. The internal plate and the external temperature probe have been applied on a north-facing wall, in order to avoid the direct solar radiation. Moreover, an infrared camera has been used to detect the existence of thermal abnormalities on the outside walls and to identify the best position for the internal heat flow meter sensor (Figure 3).

Figure 3. (**a**) Wall's thermographic investigation; (**b**,**c**) heat flow meter sensors.

Acquired measurements data have been processed by using the progressive average procedure that is based on the idea that the average of instantaneous ratios between heat flux and temperature differences on a progressively increasing time scale smoothies out the oscillations leading to the steady-state value of the thermal transmittance. The formula that describes the procedure is:

$$U_N = \frac{\sum_{j=1}^{N} q_j}{\sum_{j=1}^{N} (T_{ij} - T_{ej})} \quad (8)$$

where q is the heat flux per unit area, T_i and T_e are the internal and external temperature, respectively. Through Equation (8) it is possible to obtain the asymptotic thermal transmittance value.

3. Theoretical Performance of the Tested Walls

The buildings investigated in this study are located in central Italy and belong to different historical periods. As already mentioned they are:

- Case 1—an old building that dates back to the late 1800s, which is characterized by walls made of tuff blocks;
- Case 2—an early-1950s structure, characterized by walls made of hollow bricks and concrete;
- Case 3—a house built 15 years ago, of which walls are made of hollow bricks.

The tested walls stratigraphies are detailed in Table 1.

Table 1. Description of the studied walls.

Case 1		**Case 2**		**Case 3**	
	Thickness [m]		Thickness [m]		Thickness [m]
int	-	int	-	int	-
		Plaster	0.01		
Plaster	0.02	Hollow bricks	0.37	Plaster	0.01
Tuff blocks	0.51	Concrete	0.12	Hollow brick	0.30
Plaster	0.02	Plaster	0.01	Plaster	0.01
ext	-	ext	-	ext	-
Total thickness	*0.55*	*Total thickness*	*0.51*	*Total thickness*	*0.32*

In addition to the building's wall stratigraphy, materials thermal conductivity values are also required to calculate the thermal transmittance. The Italian Standard UNI 10351 provides thermal conductivity and conductance values of the main building materials when it is not possible to obtain direct information from the product data sheets. Starting from this information, it is possible to select between many categories for each material, characterized by different thermal properties. Table 2 lists some examples of different thermal conductivity values that can be attributed to plaster and concrete.

Table 2. Thermal conductivity of some materials by UNI 10351.

Material Type	Description	Thermal Conductivity [W/mK]
Plaster	Gypsum plaster	0.400
		0.570
	Gypsum and sand	0.800
	Concrete and sand	1.000
Concrete	Natural aggregates concrete	1.263
		1.613
		2.075
	Expanded clays concrete	0.325
		0.702
		0.914
	Autoclave cellular concrete	0.168
		0.310
	Volcanic inert concrete	0.580

Such thermal properties differences imply corresponding differences of the thermal transmittance value, which can significantly affect the design phase of a new building. On the other hand, considering existing buildings, reliable information about each single layer of the analyzed wall is needed. In most cases, the stratigraphy is deduced according to the building construction year. Moreover, the simplified procedure to label a building exclusively employs the thermal transmittance value, neglecting the information about mass density and specific heat capacity of the materials constituting the walls. In these case studies, the thermal transmittance has been calculated through the materials thermal properties provided by the UNI 10351. Cases 1 and 3 are characterized by a single value because the standard indicates that tuff has a thermal conductivity equal to 1.700 W/mK and hollow bricks—characterized by a thickness equal to 30 cm—have a thermal conductance equal to 1.163 W/m^2K. The wall of Case 2 is composed by hollow bricks and concrete. Hollow bricks (with a thickness of 37 cm) have a conductance equal to 0.935 W/m^2K but for concrete the UNI 10351 provides many thermal conductivity values. All walls are plastered on both sides but, due to the small thickness, the type of plaster does not significantly affect the results. According to this, the calculated thermal transmittance values are shown in Table 3.

Table 3. Calculated thermal transmittance considering different materials properties.

Case 1					
	Material description	Thermal conductivity [W/mK]	Thermal conductance [W/m²K]	Rs [m²K/W]	Calculated U-value [W/m²K]
int	-	-	-	0.13	
Plaster	Lime and plaster	0.700	-	-	
Tuff blocks	Tuff	1.700	-	-	**1.897**
Plaster	Lime and plaster	0.700	-	-	
ext	-	-	-	0.04	

Case 2					
	Material description	Thermal conductivity [W/mK]	Thermal conductance [W/m²K]	Rs [m²K/W]	Calculated U-value [W/m²K]
int	-	-	-	0.13	
Plaster	Lime and plaster	0.700	-	-	
Hollow bricks	Hollow bricks	0.346	0.935	-	
Concrete	Natural aggregates concrete	1.263	-	-	**0.734**
		1.613	-	-	**0.745**
		2.075	-	-	**0.754**
	Expanded clays concrete	0.325	-	-	**0.611**
		0.702	-	-	**0.695**
		0.914	-	-	**0.715**
	Autoclave cellular concrete	0.168		-	**0.504**
		0.310	-	-	**0.604**
			-	-	
	Volcanic inert concrete	0.580	-	-	**0.678**
Plaster	Lime and plaster	0.700	-	-	
ext	-		-	0.04	

Case 3					
	Material description	Thermal conductivity [W/mK]	Thermal conductance [W/m²K]	Rs [m²K/W]	Calculated U-value [W/m²K]
int	-	-	-	0.13	
Plaster	Lime and plaster	0.700	-	-	
Hollow brick	Hollow bricks	0.349	1.163	-	**0.945**
Plaster	Lime and plaster	0.700	-	-	
ext	-	-	-	0.04	

4. Results and Discussion

Measured and calculated thermal transmittance values have been obtained as detailed in the previous sections. As an example of these case studies, Figure 4 shows the asymptotic thermal transmittance value obtained for the early-1950s building.

Table 4 shows the comparison between calculated and measured values together with their percentage differences.

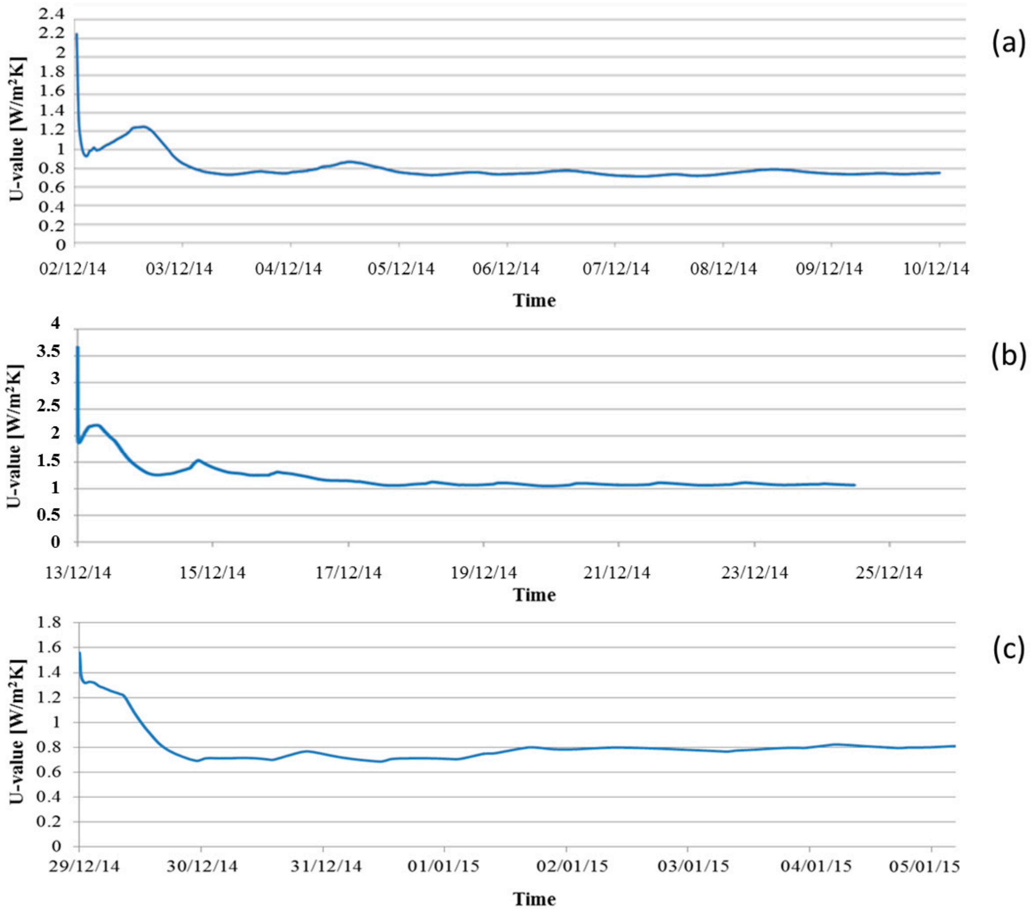

Figure 4. Thermal transmittance trend obtained by the progressive average procedure: (**a**) Case 1; (**b**) Case 2; (**c**) Case 3.

Table 4. Calculated and measured thermal transmittance values.

	Description	Calculated U-Value [W/m²K]	Measured U-Value [W/m²K]	Difference Calculated-Measured [%]
Case 1		1.897	0.750	+153
Case 2	Natural aggregates concrete	0.734	1.072	−32
		0.745	1.072	−31
		0.754	1.072	−30
	Expanded clays concrete	0.611	1.072	−43
		0.695	1.072	−35
		0.715	1.072	−33
	Autoclave cellular concrete	0.504	1.072	−53
		0.604	1.072	−44
	Volcanic inert concrete	0.678	1.072	−37
Case 3		0.945	0.810	+17

Case 1 is characterized by the highest percentage difference, equal to +153%. Probably, in this case, the wall is made of different internal materials that are not detectable by visual inspection. Another possibility is that the tuff thermal conductivity value may be significantly different from the one provided by the standard, given the wide range of values that is measured for this material [26]. Case 2 shows percentage differences that range from −53% to −30%, with an average value equal to −37%. Case 3 mismatch is the smallest one and it is equal to +17%. When we do not have reliable data arising from the product data sheets, wall's model characterized by a simple stratigraphy (such as Case 3) reduces variations induced by the material selection. The wall analyzed in Case 3 is composed of hollow bricks having a thickness equal to 30 cm, plastered on both sides. Usually, layers made of plaster are characterized by very small thicknesses compared to the wall dimensions, making the influence of the plaster thermal transmittance on the wall thermal behavior negligible. The thermal conductance of hollow bricks, according to the standard, is a function of thickness, which therefore reduces the variation in the predicted U-value. For this reason, the spread of values of the overall thermal transmittance is reduced. On the other hand, as can be seen in Case 2, a wide selection without reliable information can lead to modeling mistakes that involve high percentage differences between models and reality. Nevertheless, even simple stratigraphy can lead to incorrect results, such as Case 1. Here, the tuff thermal conductivity value is apparently overestimated. However, it is possible that the analyzed wall is made of other materials not revealed by the visual survey.

In order to compare the thermal conductivity provided by the standard to the one that fits the measured U-value, it is possible to determine the thermal conductivity of the main layer using the equation for thermal transmittance and assuming the thin plaster layers to have the thermal properties listed in Table 3. In Case 1, this provides a value of the thermal conductivity of tuff (main layer) equal to 0.461 W/mK. This value is much lower than the one provided by the standard, but it is anyway within the range of experimentally occurring values for tuff [26]. Similarly, the effective thermal conductivity of the main layer in Case 3 can be derived from the measured U-value to be 0.289 W/mK, that is in this case much closer to the value provided by the standard.

5. Conclusions

In situ thermal transmittance measurements, performed on three different building walls, have been shown. A comparison between measured and calculated values has been realized. The latter values have been determined by resorting to visual inspections, to identify wall's stratigraphy, and to the UNI 10351 Standard to establish the thermal properties of the materials constituting the walls. This Standard requires the selection between different thermal properties for a given material, affecting the value of the resulting thermal transmittance. When the standards suggest only one thermal conductivity value, the variation is reduced, such as in Case 3. However, the result of the estimation can be very different from the value obtained by measurements, such as in Case 1, where the percentage difference reaches up to +153% (that may be due to unknown stratigraphy of the inner part of the wall or to an inaccurate value of the thermal conductivity). Case 2 allows showing the material selection influence, with calculated U-values that range from 0.504 W/m^2K to 0.754 W/m^2K. In Case 2, the average percentage difference between calculated and measured U-value is equal to −37%.

The aforementioned differences between *in situ* measurements and models may not strongly influence the heating plants design because they are commonly oversized (usually this happens to overtake some criticality, such as cold bridges or improper use of heating systems). On the other hand, these differences become significant considering the building labeling, where the energy class is a function of the walls transmittance value. The U-values are often used to predict heating efficiency and to see if interventions would be cost effective. A wrong U-value could mean that dwellings are needlessly upgraded, or bad dwellings ignored.

Author Contributions

All the authors designed this research; Luca Evangelisti and Claudia Guattari performed the measurements and analyzed the data. Luca Evangelisti wrote the paper and all the authors contributed to its revision.

Conflicts of Interest

The authors declare no conflict of interest.

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