

Environmental monitoring of a Sardinian earthen dwelling during the summer season

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Abstract. Increasing interest in earth architecture has led to the development of new international norms regarding these structures. Although Italy has no specific legislation for this building type, both national laws for the safeguard of rural architecture and regional norms regarding the conservation of historical centers have considerably slowed down the pace of their destruction. This is particularly true for Sardinia, which maintains a conspicuous heritage of “raw earth” architecture, mostly in the old town centers of the Campidano plain and in its adjacent valley. Due to the current legislation on energy efficiency in buildings, it has become essential – particularly for the Sardinian region – to define guidelines for the improvement of energy efficiency for this existing building heritage and identify the best parameters for their energetic classification. Currently, these constructions are heavily penalized by the gap that persists between the requirements of current energy balance evaluations, calculated upon heating and domestic hot water energy demands, and the actual year-round energy performance, which also includes the summer season. Moreover, this building type has a low lifecycle environmental impact, but this aspect is not properly “rewarded” by Italian regulations. The study proposed herein firstly took into account the simulation of the thermal transient characteristics of the adobe wall (brick made of clay, earth and straw, forged with wooden molds and sun dried). Analytical calculations were performed using a transient model, assuming sinusoidal behavior of all the parameters acting on the system. The results showed a high thermal inertia of the material and a good ability in dampening the external thermal wave. Next, we conducted an internal and external environmental monitoring of an existing earthen residential building in Sardinia (“Casa Mancosu”, Serramanna, VS), which provided the experimental data for the evaluation of the whole building thermo-physical behavior. The measurements were taken during the 2010 summer season; the dwelling was not cooled by an air conditioning system. Thermal comfort analyses based on these experimental data indicate that the roof is the “weak” component, creating local discomfort due to radiant asymmetry. The described methodology is expected to be applicable also to the many buildings of this geographical area similar to the examined one.

1. Introduction

1.1 Earth architecture: the state of the Legislations

Current Italian norms referring to earth architecture lay out regulations for the conservation of rural architecture (Law 378/2003) and the enhancement of value of existing earthen architectures (Regional Law 2/2006, Piemonte, and Regional Law 17/1997, Abruzzo). These three laws have attempted to fill the legislative void for the conspicuous heritage of raw earth architecture, favoring the safeguard of this architectural patrimony in Italy and particularly in Sardinia, where the adobe (from the Arab *al-tub*, brick) building technique is very common. The sole interest of these legislative texts is the safeguard and conservation of buildings of rural and historical importance: a conservationist slant that neither encourages new constructions nor incentivizes the renovation of existing earth buildings in a territory where this is a well rooted building technique. The renewed national and international interest in earth architecture is not only tied to criteria of bio-architecture but is dictated first and foremost by its thermo-physical characteristics that meet the demands of a Mediterranean climate, particularly



during the summer season [1-2].

Although new laws have been proposed in Italy in the last few years [3-5], there has been no positive outcome due to the absence of specific references to the construction technique and of technical elements to support the use of raw earth buildings rather than those built using other materials [6]. On the international front, many countries have legislated on the matter (see Figure 1). A picture on the legislative situation regarding earth construction in the world is given in [7]. This study has evidenced how 79% of norms analyzed worldwide focus on the construction technique most prevalent in the respective territories. Indeed in many countries adobe masonry is considered a weight-bearing structure, whereas Italian legislature does not include raw earth among construction materials [8], thus discouraging research and experimentation of building types associated to these techniques.

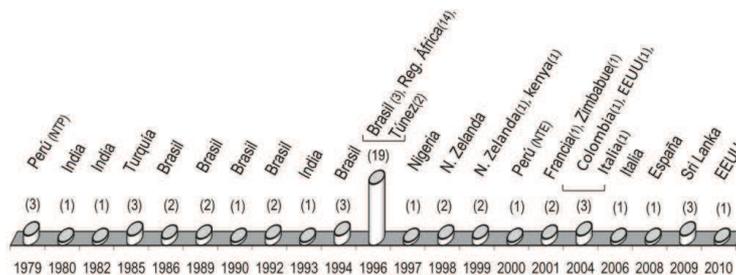


Figure 1. History of laws concerning earth constructions published worldwide [7].

The building type is also unfavorably treated by the Italian normative context, which is still lacking in norms regarding energetic classification of buildings in summertime conditions. The time has come to investigate which types of buildings best respond to Mediterranean climatic conditions, to limit summertime energy consumption. The scientific results collected through environmental monitoring of the buildings should form the basis of the passive requisites to be introduced in current national laws regarding energy efficiency.

With [9] Italy has acknowledged the European Guideline 2002/91/EC, substituted by the current 2010/31/EU, which promotes the improvement of energy efficiency performance in buildings within the Union, taking into account local external climatic conditions. As far as the summertime aspect is concerned, with the introduction of [10], Italian legislation has begun to define the performance limits for summertime cooling, introducing parameters to determine the cooling energy requirement of the building opaque envelope and outlining specific requisites on its periodic thermal transmittance (Y_{ie}) and surface mass (M_s). These parameters are also included in the evaluation dictated by the National Guidelines [11], with energy classes from I to IV, according to the degree of quality of energy performance reached.

These prescriptions make it possible to determine adequate thermal performance in summertime conditions, so the dampening and attenuation of the external thermal wave can become a controlled value even in the planning phase of the buildings in question.

To date, however, summertime performance does not contribute to the definition of a global energetic efficiency class of the building, but is reported by means of separate indicators in the energy efficiency certification document, named "Attestazione di Prestazione Energetica" (APE). Given Italy's climate conditions, it is important to obviate this shortcoming and to reward, through the APE certification, those buildings which maintain suitable levels of comfort with a reduced use of air cooling and dehumidification systems [12].

1.2 Objectives

This article presents the case study of an adobe building monitored in Sardinia during the summer season. Firstly, the article tackles, using the methodology described in the paragraph below, the effective thermal inertia of an adobe wall, based on its physical characteristics, tightly connected to the time constant of the building. Useful indications in terms of comfort are expected, so that minimum

passive requisites can be suggested for introduction in the legislation on building summertime performance.

Environmental monitoring of the private residential building, “Casa Mancosu” [13], built in adobe and situated in the historical town center of Serramanna (VS), Italy, has provided all the necessary data to apply the technical standards ISO 7730:2005 [14] and ISO 7726:1998 [15], needed for the evaluation of thermal comfort levels in the monitored indoor environments. The analysis of thermal comfort according to these norms allows to classify the environment, according to 3 comfort classes, and identify the inefficient components of the building, responsible for creating conditions of local discomfort.

2 Analytical evaluation of the thermal behavior of adobe masonry

2.1 Set up and resolution of the problem

The initial study of the thermal behavior of an adobe monolayer wall in dynamic regime was tackled assuming that the indoor temperature ($T_{w,indoor}$) is measured, considering outdoor conditions, air temperature ($T_{a,out}$) and solar radiation (W), on an hourly basis [16].

In line with the measured values, let us consider the law of temporal variation of outdoor temperature by approximating it to a sinusoidal curve of period (P) equal to 24 hours:

$$T_{a,out} = T_{a,mean\ out} + \theta \cos(2\pi t/P) \quad (1)$$

Solar radiation is also assumed to follow a sinusoidal trend.

Given the Fourier equation for conduction, simplified for one-dimensional conditions in space:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (2)$$

we simplify the study of the temperature variation inside the masonry, assuming that the latter is given by the product of the functions $A(x)$ dependent on space and $B(t)$ dependent on time, according to the technique of separation of variables:

$$T(x, t) = A(x)B(t) \quad (3)$$

To calculate the constants, which we will call M and N , the following boundary conditions were set:

$$T(x = 0) = T_{w,indoor} \quad (4)$$

$$\left(\frac{\partial T}{\partial x}\right)_{x=d} = -\frac{1}{\lambda} [aW + h_c(T_{a,out} - T_{w,out}) + h_r(T_{sky} - T_{w,out})] \quad (5)$$

From the resolution of the system, we obtain:

$$T(x, t) = \left(Me^{\sqrt{\frac{i\omega}{\alpha}}x} + Ne^{-\sqrt{\frac{i\omega}{\alpha}}x} \right) e^{i\omega t} \quad (6)$$

where the constants M and N depend on known quantities:

$$M = \frac{T_{w,indoor} \sqrt{\frac{i\omega}{\alpha}} e^{-\sqrt{\frac{i\omega}{\alpha}}d} - \frac{aW}{\lambda} + \frac{h_c}{\lambda} \left(T_{w,indoor} e^{-\sqrt{\frac{i\omega}{\alpha}}d} - T_{a,out} \right) + \frac{h_r}{\lambda} \left(T_{w,indoor} e^{-\sqrt{\frac{i\omega}{\alpha}}d} - T_{sky} \right)}{\sqrt{\frac{i\omega}{\alpha}} e^{\sqrt{\frac{i\omega}{\alpha}}d} + \sqrt{\frac{i\omega}{\alpha}} e^{-\sqrt{\frac{i\omega}{\alpha}}d} - \frac{h_c}{\lambda} \left(e^{\sqrt{\frac{i\omega}{\alpha}}d} - e^{-\sqrt{\frac{i\omega}{\alpha}}d} \right) - \frac{h_r}{\lambda} \left(e^{\sqrt{\frac{i\omega}{\alpha}}d} - e^{-\sqrt{\frac{i\omega}{\alpha}}d} \right)} \quad (7)$$

$$N = \frac{T_{w,indoor} \sqrt{\frac{i\omega}{\alpha}} e^{\sqrt{\frac{i\omega}{\alpha}}d} + \frac{aW}{\lambda} + \frac{h_c}{\lambda} \left(T_{a,out} - T_{w,indoor} e^{\sqrt{\frac{i\omega}{\alpha}}d} \right) + \frac{h_r}{\lambda} \left(T_{sky} - T_{w,indoor} e^{\sqrt{\frac{i\omega}{\alpha}}d} \right)}{\sqrt{\frac{i\omega}{\alpha}} e^{\sqrt{\frac{i\omega}{\alpha}}d} + \sqrt{\frac{i\omega}{\alpha}} e^{-\sqrt{\frac{i\omega}{\alpha}}d} - \frac{h_c}{\lambda} \left(e^{\sqrt{\frac{i\omega}{\alpha}}d} - e^{-\sqrt{\frac{i\omega}{\alpha}}d} \right) - \frac{h_r}{\lambda} \left(e^{\sqrt{\frac{i\omega}{\alpha}}d} - e^{-\sqrt{\frac{i\omega}{\alpha}}d} \right)} \quad (8)$$

Function (6) represents the solution to the Fourier equation in periodic dynamic regime. Let us add now the steady-state solution:

$$\langle T \rangle = c_1 x + c_2 \tag{9}$$

where c_1 and c_2 depend on the mean values of the oscillating functions and on the wall thermal transmittance (U -value):

$$c_1 = \frac{T_{w,out} - T_{w,indoor}}{d} = \frac{U}{\lambda} (T_{a,mean\ out} - T_{a,indoor}) \tag{10}$$

$$c_2 = T_{w,indoor} \tag{11}$$

The general solution will therefore be given by:

$$\Theta(x, t) = \left(M e^{\sqrt{\frac{i\omega}{\alpha}} x} + N e^{-\sqrt{\frac{i\omega}{\alpha}} x} \right) e^{i\omega t} + c_1 x + c_2 \tag{12}$$

The real part of the complex function (12) represents the temperature at different locations within the wall (variable x) and at different times (variable t).

The main limit of this calculation lies in the assumption of sinusoidal trend for the external climatic variables, thus an approximation of the real profiles.

2.2 Application to the adobe wall

The application of the analytical solution (12) enables us to confirm the good inertial behavior of adobe. Figure 2 depicts the temporal evolution of temperature at different positions within a 40 cm thick adobe masonry wall (position $x=0$ refers to the internal wall surface, $x=0.4$ m to the external one). The utilized thermo-physical properties of the material are reported in Table 1, together with the corresponding source.

Table 1. Thermo-physical properties of adobe.

Property	Unit	Value
Mass density	kg/m ³	1842 [17]
Thermal conductivity (λ)	W/(m K)	0.663 [17]
Specific heat	J/(kg K)	1000 [18]
Thermal diffusivity (α)	mm ² /s	0.3599

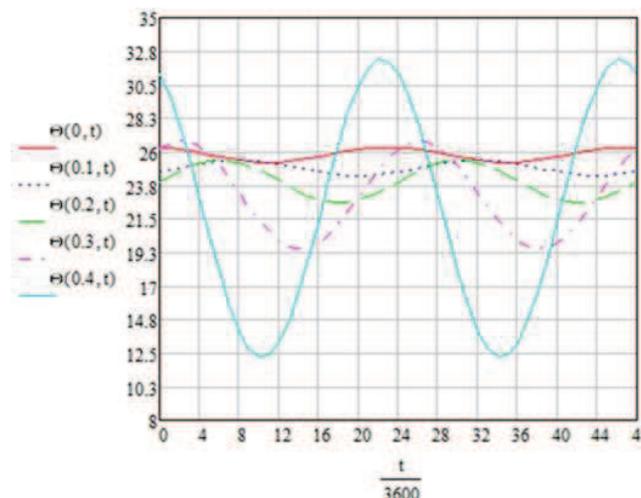


Figure 2. Temporal evolution of temperature inside an adobe masonry wall.

As expected, it can be noted that the external thermal wave increasingly lags out of phase and attenuates as we advance in the masonry towards the inside of the building; at a depth of 30 cm, the temperature is already almost constant, with oscillations of approximately 1 K, notwithstanding elevated thermal excursions (around 20 K).

From Figure 2, we can deduce that the phase displacement is above 12 hours, corresponding to a Class I performance according to the National Guidelines [11]. Applying the standard ISO 13786 [19], we obtain the dynamic thermal characteristics reported in Table 2.

Table 2. Dynamic thermal characteristics of adobe-made walls, according to [19].

<i>Parameter</i>	<i>Unit</i>	<i>Value with d=30 cm</i>	<i>Value with d=35 cm</i>	<i>Value with d=40 cm</i>
Periodic thermal transmittance (Y_{ie})	W/(m ² K)	0.347	0.210	0.127
Decrement factor (f_d)		0.216	0.146	0.098
Phase shift (φ)	H	11.0	12.9	14.8
Surface mass (M_s)	kg/m ²	553	645	737

All these data suggest that an environment with at least 30 cm of adobe masonry can provide satisfactory thermal comfort conditions in summertime if all the other components of the building envelope behave efficiently. This result is confirmed by a large quantity of data present in the literature, amongst which it is worth mentioning [20], an interesting analysis on the thermodynamic behavior of a raw earth structures.

3 Environmental monitoring of the case study

3.1 Analysis of the hygrothermal comfort of an earth building

The environmental monitoring of a real case study allowed us to perform an analysis of hygrothermal comfort in an indoor environment built using the adobe technique. The analysis was conducted using the classic Fanger's method [21], although – strictly speaking – this is quantitatively correct only for spaces in which the use is passive, in other words where there is no intervention by occupants on the building system to improve their level of comfort. The results will therefore be taken as simple qualitative indicators to shed light on the most critical elements of the structure and point towards possible interventions for energetic-environmental retrofit.

The monitoring of “Casa Mancosu” was conducted using two microclimatic control units (fitted with hot filament anemometer, global thermometric probe, and psychrometer) and appropriate temperature and humidity sensors, in accordance with the standard [15]. In addition to the measurements prescribed by this norm, all the temperatures of the internal vertical walls, floors and ceilings enclosing the spaces were also measured, using contact thermal resistances. The measurement chain was completed by a portable computer and a data logger. The data necessary to ascertain the level of thermal satisfaction are the indoor air temperature ($T_{a,indoor}$), the relative humidity of indoor air (RH_i), the indoor air velocity (v_{ar}), the mean radiant temperature (T_r), the type of clothing worn by the occupants (I_{cl}), and the metabolism according to the performed activity (M^*).

The experimental data were recorded at 10-minute intervals by the microclimatic units (positioned in the most significant places, according to frequent occupant activities), subdividing the 24-hour period into 4 subgroups of 6 hours for the living room (floor area: 24.5 m²) and 6 subgroups of 4 hours for the bedroom (floor area: 14.7 m²). This way of grouping the data was established following the positive verification of the cyclical temperature variations indicated in the standard [14], which specifies that if the peek-to-peek variation is lower than 1 K and the rate of temperature variation in response to a step input is less than 2K/h, the methods for steady-state regime can be applied.

The case-study building has a residential use and the monitored period was the summer season; for this reason, the following values were assumed: $M^*=70$ W/m² (or 1.2 met) and $I_{cl}=0.5$ clo.

The method prescribed by the technical standard is applicable, as the following conditions subsist: 46 W/m² < M^* < 232 W/m² (0.8 met < M^* < 4 met), $0 < I_{cl} < 0.310$ m²K/W ($0 < I_{cl} < 2$ clo), $10^\circ\text{C} < T_{a,indoor} < 40^\circ\text{C}$, $0 < v_{ar} < 1$ m/s, and $0 < p_a < 2700$ Pa.

The performed calculations of the global values PMV (Predicted Mean Vote index) and PPD (Predicted Percentage of Dissatisfied people) were validated by means of the test specified in [14].

Analytical determination of thermal comfort must be completed by the analysis of phenomena associated to local discomfort, that is to say drafts (DR), vertical air temperature variation ($\Delta T_{a,v}$), hot/cold floors (T_{pav}), radiant asymmetry (AR). The analysis of the latter characteristic, in particular, is useful to highlight shortcomings in the thermal behavior of the construction elements of the building.

Local discomfort due to radiant asymmetry is caused by an excessive temperature difference between opposite surfaces (roof or walls), too hot or too cold. To determine the degree of this discomfort, it is necessary to calculate the difference in radiant temperature along the flat plane between opposite and parallel surfaces (ΔT_{pr}).

According to [15], T_{pr} is calculated as follows:

$$T_{pr} = T_1^4 * F_{p-1} + T_2^4 * F_{p-2} + \dots + T_N^4 * F_{p-N} \quad (13)$$

This relationship is valid if all surfaces forming the environment are black bodies. However, the calculation is significant, because the materials used in the case-study building present emissivity values (at infrared wavelengths) close to one, as most of the construction materials.

The building was subject to the verification of all the indices of local discomfort, both in the living room and in the bedroom. In particular, to verify the degree of radiant asymmetry, the most critical thermal situation was chosen. For the living room, where a large glass surface contrasts an opaque indoor surface, the calculation along the horizontal plane (wall-wall) is reported; on the contrary, for the bedroom, the vertical direction was chosen (floor-roof), because the monitoring concerned the summertime period and – again in accordance with [14] – the percentage of local thermal discomfort caused by the “hot roof” situation is greater than that caused by a “hot wall”.

3.2 Thermal comfort analysis results

The analysis of thermal comfort in “Casa Mancosu” relates to sedentary activity: in the living room area we refer to a person sitting in a state of relaxation; the bedroom, on the other hand, has been divided in two sections: one related to a person in the “study” position and one related to the “sleeping” position, as suggested by [22]. This distinction between daytime and nighttime allows a more complete outlook of comfort conditions throughout the whole day.

As shown in Figure 3, the living room performs with a good comfort class during occupancy, with PPD above 15% for only 2.2% of the recorded data. Considering the summertime monitoring, the construction elements making up this envelope and its favorable south-east orientation do not call for energy optimization intervention.

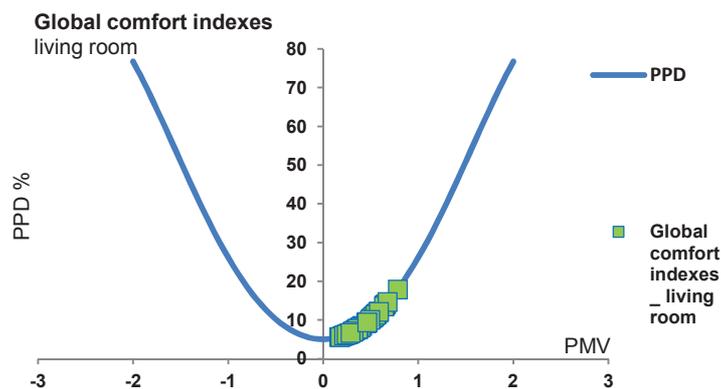


Figure 3. Global comfort indices in the living room of “Casa Mancosu” (summertime monitoring).

The bedroom, on the other hand, does not fit the conditions of thermal comfort. The major discomfort – according to calculations made in line with the technical standard – is caused by the roof covering, which has a negative effect particularly during the sleeping hours, as evidenced by the comparison of Figures 4 and 5. Indeed, the graph in Figure 5 shows a higher dissatisfaction

percentage, together with an increase of the higher PPD values, from 30% to over 40%, highlighting the importance of better comfort conditions in the hours dedicated to sleep.

Adobe’s high thermal inertia guarantees almost constant temperatures in indoor environments, while local discomfort is caused by other weak components of the construction, such as the roof covering and windows lacking external sun screens, as evident by indoor air and surface temperature measurements (see Figures 6 and 7).

Figure 8 illustrates the results of verifications of discomfort due to radiant asymmetry for “hot wall” in the living room (the negative values mark the absence of discomfort conditions). Figure 9 shows instead the verifications of radiant asymmetry in the bedroom for the “hot wall” and “hot ceiling”: in this case, discomfort caused by “hot wall” is present, though not significant, whereas the incidence of discomfort caused by the roof, combined with the global PMV and PPD values, places this environment in borderline comfort conditions or in total discomfort, according to [14].

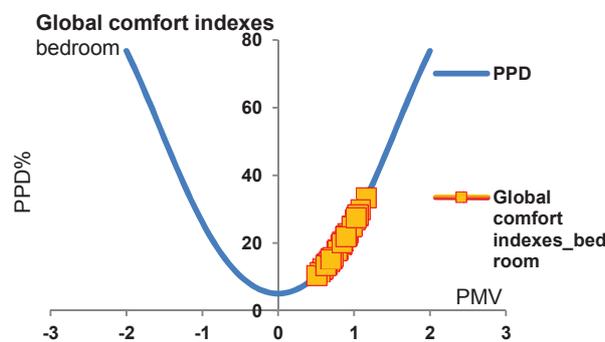


Figure 4. Global comfort indices for the bedroom of “Casa Mancosu” (daytime monitoring).

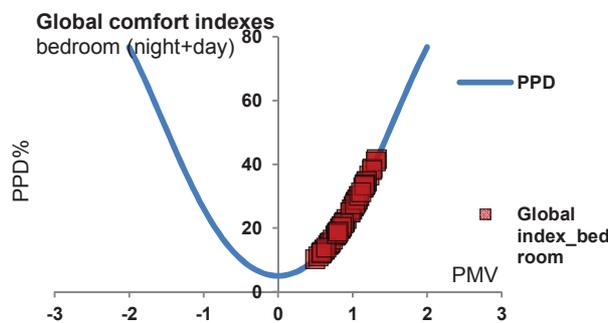


Figure 5. Global comfort indices for the bedroom of “Casa Mancosu” (24-hour monitoring).

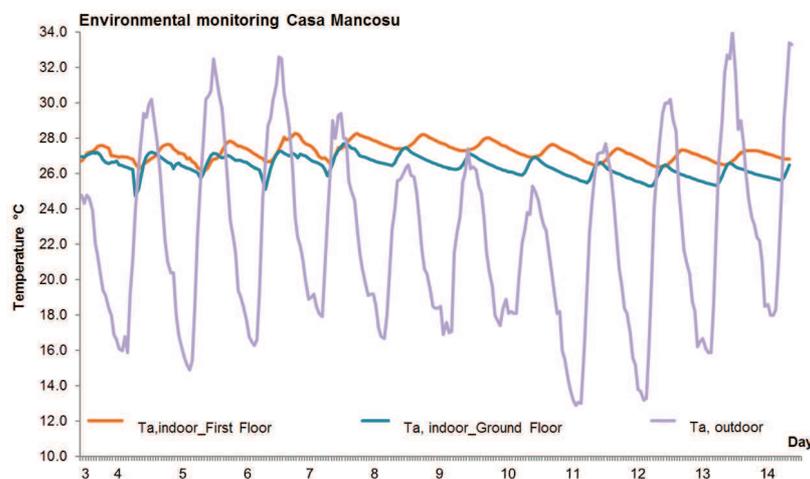


Figure 6. Monitored outdoor and indoor air temperatures (July 30 – August 10, 2010).

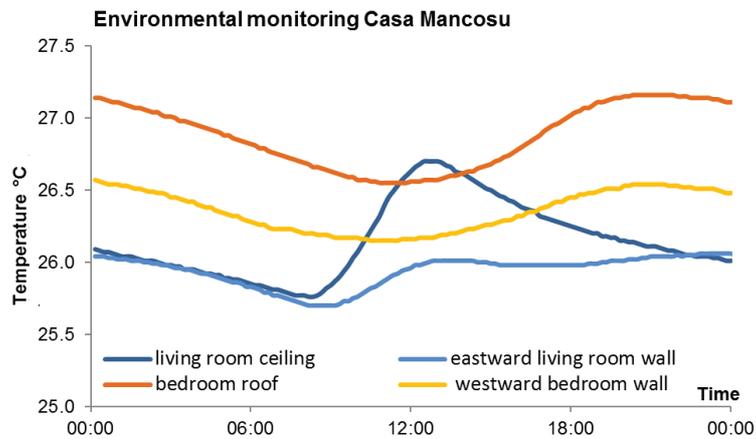


Figure 7. Monitored indoor surface temperatures (August 8, 2010).

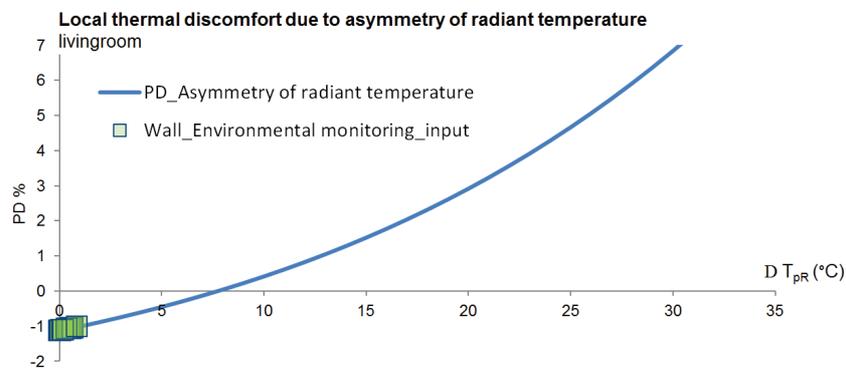


Figure 8. Local thermal discomfort due to asymmetry of radiant temperature in the living room (“hot wall” case).

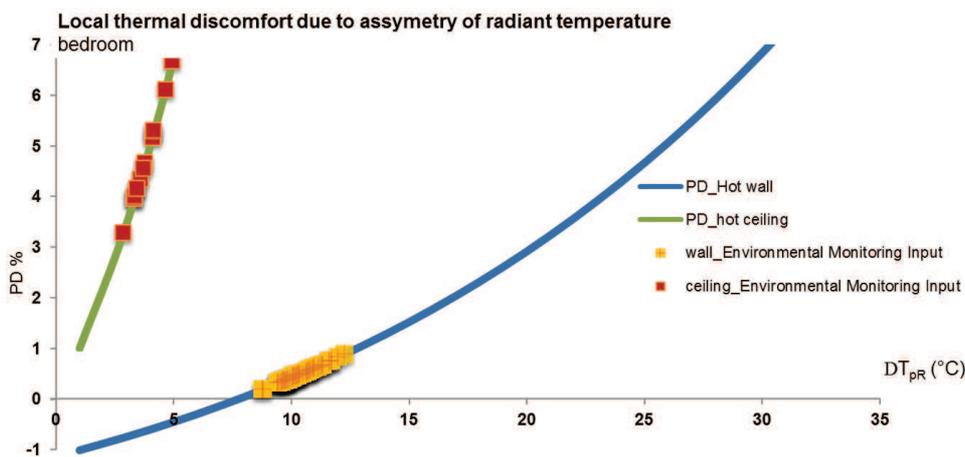


Figure 9. Local thermal discomfort due to asymmetry of radiant temperature in the bedroom (“hot wall” and “hot ceiling”).

4. Conclusions and future developments

In the present paper, we employed methodologies capable of evaluating the thermodynamic behavior of a raw earth construction and the hygrothermal comfort perceived within the adobe private residential building “Casa Mancosu”. The results confirm the high thermal inertia given by the thermo-physical properties of the adobe material. We verified the level of thermal comfort of the case-study building, calculated according to current international standards, using the experimental data

from the environmental summertime monitoring. More specifically, the adobe-made building, without mechanical cooling, has proven to be able to maintain satisfactory levels of thermal comfort and internal temperatures close to the design set points of air conditioning systems. On the other hand, conditions of thermal discomfort were recorded in the presence of inefficient construction elements. Specifically, the presented graphs highlight how the roof of “Casa Mancosu” – which does not reach the periodic thermal transmittance currently prescribed by Italian legislation – causes discomfort due to radiant asymmetry between ceiling and floor and a high predicted percentage of dissatisfied people (above 15% for as many as 83% of the recorded data).

As a future development, we suggest to perform a full dynamic analysis of the building thermal evolution, which could be properly validated by means of the monitoring data and used to simulate possible retrofit actions – such as roof insulation and venting – in a frame of reliability. As for the evaluation of comfort levels, we suggest further analyses using the adaptive method [2], due to the mentioned limits of the Fanger’s method.

Finally, a comparison between cooling energy needs obtained by monthly-based methods (implemented by current technical standards [23]) and monitoring results is expected to shed some light on the inaccuracy of quasi-steady-state energy calculations for the summer period.

Acknowledgments

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List of symbols

a	external wall radiative absorption coefficient
d	wall thickness [m]
F_p	view factor
h_c	external convective heat transfer coefficient [W/(m ² K)]
h_r	external radiative heat transfer coefficient [W/(m ² K)]
I_{cl}	clothing insulation [m ² K/W, clo]
M^*	metabolic rate [W/m ² , met]
P	period of the external air temperature wave [s]
p_a	vapor pressure [Pa]
PMV	Predicted Mean Vote index
PPD	Predicted Percentage of Dissatisfied people index
RH_i	indoor air relative humidity [%]
t	time [s]
$T_{a,indoor}$	indoor air temperature [°C]
$T_{a,out}$	external air temperature [°C]
$T_{a,mean out}$	mean external air temperature [°C]
T_{pr}	radiant temperature along the flat plane
T_r	mean radiant temperature [°C]
T_{sky}	equivalent sky temperature [°C]
$T_{w,indoor}$	indoor surface temperature [°C]
$T_{w,out}$	outdoor surface temperature [°C]
U	wall thermal transmittance [W/(m ² K)]
v_{ar}	indoor air velocity [m/s]
W	solar radiation [W/m ²]
x	spatial coordinate [m]

Greek symbols

α	wall thermal diffusivity [m^2/s]
λ	wall thermal conductivity [$\text{W}/(\text{m K})$]
θ	semi-amplitude of the external air temperature wave [K]
Θ	wall temperature field [$^{\circ}\text{C}$]
ω	angular frequency of the external air temperature wave [rad/s]

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