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Thermal inertia of heavyweight traditional buildings: experimental measurements and simulated scenarios

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Abstract

This paper discusses the results of an experimental campaign aimed to describe the thermal performance of a traditional building located in Catania, Southern Italy. The building was built in the early 1900s with traditional techniques and local materials, namely basalt stones, and is currently used for residential purposes.
The results of the experimental campaign are exploited to calibrate a model for the dynamic simulation of the building with DesignBuilder. The calibrated model is then used to simulate how the same building would behave with a modern envelope made of a double leaf of bricks; other simulations take into account possible retrofit solutions, such as the installation of an insulating material either on the inner or the outer side of the walls, as well as the role of nighttime natural ventilation.

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Keywords: thermal inertia; basalt stones; natural ventilation; dynamic simulations.

1. Introduction

Traditional and historic buildings in warm climates, such as in the Mediterranean area, typically show thick and massive walls made of local stones, which provide them with high thermal inertia. This feature allows these buildings to be resilient to the outdoor climate, especially in summer, when they can provide good indoor thermal

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Nomenclature

c_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
DF	decrement factor (-)
R	thermal resistance ($m^2 \cdot K \cdot W^{-1}$)
s	thickness (m)
T	temperature (°C)
TL	time lag (h)
U	thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	density ($kg \cdot m^{-3}$)

comfort despite the severe heat waves experienced outdoors.

Several authors have studied and emphasized the thermal performance of traditional massive buildings in the Mediterranean area. Gagliano et al. carried out an experimental campaign to assess the transient behaviour of the massive walls of a historic building located in Southern Italy, dating to the end of the 1800s [1]. The walls are built with roughly squared blocks of basalt stones, and their thickness is of about 1.00 m. The study showed that the thermal inertia of the walls is significantly affected by the exposure (East or West) and by the exploitation of nighttime ventilation; the latter allows to effectively discharge the heat stored in the massive walls.

Cardinale et al. studied the thermal performance of two types of vernacular buildings (Sassi of Matera and Trulli of Alberobello), that are peculiar to some restricted zones in Southern Italy [2]. In this case, the walls are respectively made of sandstone and limestone, with a thickness ranging from 50 to 90 cm. In both cases, the experimental measurements highlighted that the indoor temperature in summer seldom exceeds 28°C, thus providing excellent thermal comfort, also thanks to natural ventilation.

On the other hand, Martin et al. measured the indoor temperature in a traditional building located in a village in central Spain, and compared the results with those recorded in a wooden house located in the same village [3]. The outer envelope of the traditional building is made of local stones, with a thickness of around 50 cm. In summer, the traditional stone house did not suffer from overheating: indeed, the peak indoor temperature was 27.5°C, which means around 9°C lower than in the wooden house.

Stazi et al. compared, by means of experimental measurements and dynamic simulations, the thermal performance of several wall configurations in temperate climates, including a traditional massive wall with a single layer of solid bricks and a more modern uninsulated brick-block cavity wall [4]. The outcomes of this study show that, in hot summer days, the internal surface temperature of the traditional massive wall can be up to 5°C lower than for the modern envelope, thus providing better thermal comfort indoors. However, when applying a 9-cm insulating layer to the traditional envelope, in order to improve the building performance in winter, the internal surface temperature may increase by around 3°C, especially with the insulation on the inner side. The only solution to improve summer thermal comfort while also insulating traditional massive walls is to leave a ventilated air cavity between the solid bricks and the outer insulation layer. Air ventilation in the cavity should obviously be prevented in winter [5]. Uninsulated massive walls also provide high thermal capacity in relation to internal loads, such as people, appliances and solar gains. However, internal insulation considerably affects this property, thus causing severe overheating in summer ([6], [7]).

However, in the last decades, there has been a transition from traditional massive buildings to lightweight envelopes; these are provided with a considerable thickness of insulating material that acts as a barrier against the outdoor climatic conditions. Even in case of retrofit of historic buildings, designers usually aim at providing insulation, often pushed by regulatory requirements, and do not consider the negative effects induced on the inertial capacity of the envelope. This issue may be particularly worrying if one takes into account the climate changes that are going to be experienced in the 21st century. Several studies foresee an increase by 1.5°C in annual mean temperature by 2050 and 3–4°C by 2100 in the Mediterranean area, under the assumption that the atmospheric concentration of carbon dioxide will increase up to 700 ppm by 2100 [8]. In temperate climates, this will produce a substantial shift from heating energy to cooling energy in buildings [9].

In this context, this paper shows the results of an experimental campaign to describe the thermal behaviour of a traditional building in Southern Italy. Then, a series of dynamic simulations, based on a calibrated model, describes the effects of potential retrofit solutions, such as the installation of an insulating material either on the inner or on the outer side of the walls. The role of nighttime natural ventilation is also investigated.

2. Case study

The building selected as a case study is located in Catania (Southern Italy). It was built at the beginning of the 1900s and its walls consist of a single layer of roughly cut basalt stones and mortar (70 cm), plus the inner and outer layers of lime-based plaster. This construction technique was very widespread in Catania up to the end of the '50s, and it is still quite common, due to the great availability of basalt stones originated from remote eruptions of the volcano Etna. Basalt stones provide high thermal inertia, which is particularly suitable for the climate of this area; indeed, the summer season is quite long and hot, with peak daily outdoor temperatures that may easily exceed 35°C. The building has three floors; the analysis is concentrated on the top floor, which is covered by a sloping roof with cotto tiles. Figure 1 shows the room where experimental measurements have been performed; this room has the only outside surface facing South.

In both cases, the thermal resistance associated with the inner and the outer convective-radiant heat transfer is 0.13 and 0.04 $m^2·K·W^{-1}$, respectively. As a result, the U-value is 1.7 $W·m^{-2}·K^{-1}$ for the traditional massive wall and 1.1 $W·m^{-2}·K^{-1}$ for the brick wall.

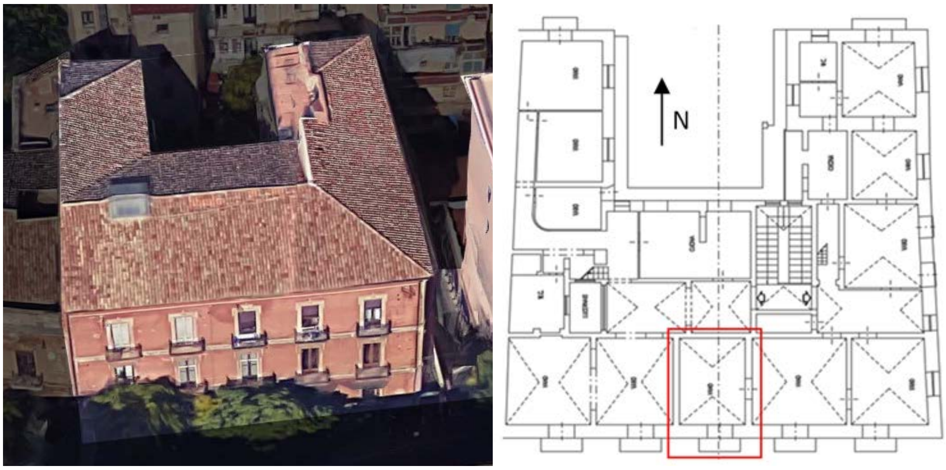

Fig. 1. Building selected as a case study: aerial view and plan of the second floor

Table 1. Thermophysical properties of the outside walls

	s [m]	λ [$W·m^{-1}·K^{-1}$]	ρ [$kg·m^{-3}$]	c_p [$J·kg^{-1}·K^{-1}$]
Traditional wall: basalt stones + mortar (U = 1.7 $W·m^{-2}·K^{-1}$)				
Plaster	0.025	0.7	1400	1090
Basal stones with mortar	0.7	2.0	2000	900
Plaster	0.025	0.7	1400	1090
Modern envelope: double brick with air gap (U = 1.1 $W·m^{-2}·K^{-1}$)				
Plaster	0.02	0.7	1400	1090
Hollow bricks	0.12	0.39	720	840
Unventilated air gap		R = 0.18 $m^2·K·W^{-1}$		
Hollow bricks	0.08	0.39	720	840
Plaster	0.02	0.7	1400	1090

On the other hand, Table 1 shows the thermophysical properties of the outside walls of the selected building. It is interesting to remark that the value retained for the thermal conductivity of basalt stones is lower than what suggested in the literature (λ = 2.9 $W \cdot m^{-1} \cdot K^{-1}$), to take into account the presence of a non-negligible quantity of mortar. Table 1 also describes the stratigraphy of a modern wall, characterized by two layers of hollow bricks: this typology of wall has been widely used in the last forty years in Italy, with an increasing thickness of insulating material being introduced in the gap, starting from the ’90s. This modern envelope solution will be considered in the paper, to allow a performance comparison in terms of inertia and thermal comfort in summer.

3. Methodology

3.1. Experimental measurements

The monitoring campaign was performed in the room indicated in Fig. 1 from 15 June 2016 to 22 August 2016. However, the measurements were interrupted from the 3rd to the 11th of July, due to a technical problem.

In order to study the thermal performance of the massive wall, and its influence on the indoor thermal comfort, the following parameters were measured:

- Indoor air temperature in the center of the room
- Relative humidity in the center of the room
- Outdoor air temperature
- Inside and outside surface temperatures of the south facing wall
- Air velocity in the center of the room

To this aim, a TESTO 480 data logger was used, equipped with suitable probes to measure air temperature and air velocity. On the other hand, the surface temperatures were measured by two thermocouples connected to an LSI Lastem data logger. In both data loggers, an acquisition rata of five minutes was set.

During the measurement campaign, the test room was not occupied, and no internal gains were observed. Only occasionally did the occupants use the adjacent room, which is separated from the test room by an arched doorway. The white curtains, placed on the inner side of the windows, were constantly keep closed. The outside shading systems, needed to protect from direct solar radiation, were partially closed. Finally, no air-conditioning system was activated.

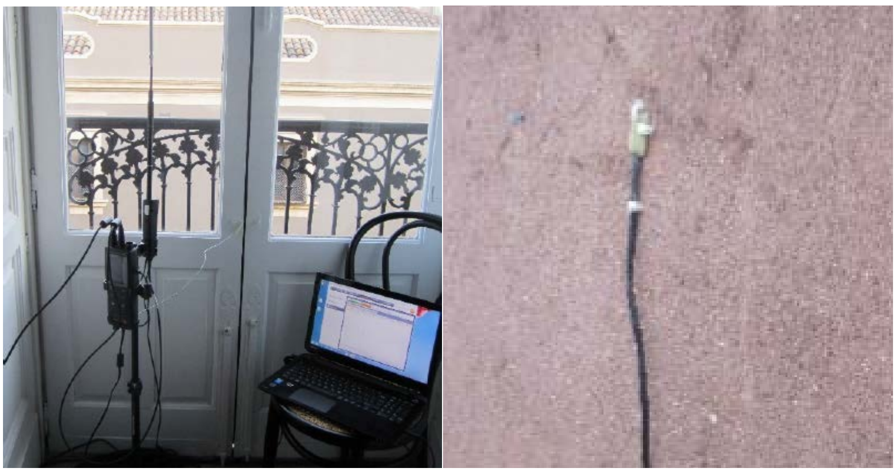

Fig. 2. TESTO 480 data logger (left) and probe to measure the outer surface temperature (right)

3.2. Assessing the thermal inertia of the walls

While the acquisition of the indoor air temperature is useful to evaluate the indoor thermal comfort, the measurement of the surface temperatures allows to assess the thermal capacity of the massive wall. In particular, in order to quantify the thermal inertia of walls, the time lag (TL) and the decrement factor (DF) are commonly used.

Their definition can be stated in relation to a periodical heat wave propagating through the wall. Under this assumption, the time lag (TL) is the time shift between the occurrence of the maximum temperature on the outer and the inner surface, and is measured in hours. On the other hand, the decrement factor (DF) can be defined as the ratio of the amplitudes of the inner and the outer surface temperature fluctuations. Even if the actual forcing conditions acting on the wall (outdoor air temperature, solar irradiance) are not exactly periodical, they still present fluctuations based on a daily cycles. Hence, the above-mentioned concepts were easily applied to the experimental results.

It is here interesting to remind that the theoretical values of both time lag and decrement factor can be assessed analytically through a procedure described in the standard UNI 13786 [10], based only on the data reported in Table 1. For the walls made of basalt stones, such theoretical values would be TL = 18.7 h and DF = 0.02. However, the analytical procedure applies under sinusoidal conditions, which is far from reality. The comparison between theoretical and real values of TL and DF will be discussed in Section 4.1.

3.3. Dynamic energy simulations

After processing the experimental data, which allows to describe the performance of the selected historic building, a series of dynamic simulations was performed by using Design Builder, a well-known tool based on the calculation engine of Energy Plus. The simulation model prepared on Design Builder was first calibrated by comparing the simulated indoor air temperature and surface temperatures with the experimental data; then, it was used to carry out further analyses.

In particular, a first series of simulations made it possible to make a comparison between the current performance of the building and the theoretical performance of the same building having a modern envelope, made of two layers of hollow bricks with an unventilated air gap (see Table 1). In this case, in order to perform the comparison under the same U-value, a 2-cm layer of EPS ($\lambda = 0.04\ W \cdot m^{-1} \cdot K^{-1}$, $\rho = 25\ kg \cdot m^{-3}$) was applied to the massive basalt walls, either on the inner or on the outer side of the wall. This allowed investigating the different behaviour in terms of thermal inertia, as well as the role played by the position of the insulating material. Then, in a second series of simulations, the exploitation of nighttime ventilation was also considered; in this case, the 50% of the glazed surface in the test room was kept open from 00:00 to 06:00. Under this hypothesis, Design Builder is able to calculate the rate of incoming air as a function of the wind pressure acting on the building surface (Calculated ventilation).

Figure 3 reports a sketch of the model built on Design Builder. As shown, the model includes not only the test room, but also the adjacent zones. All zones identified by dark grey color were simulated as adiabatic, since they have the same exposure and the same profile of occupancy as the test room. In the simulations, the solar absorptance of all outer surfaces was set to 0.6; the solar transmittance of the internal white curtains is 0.75. A constant rate of infiltration as high as 0.25 ACH was also considered, which provided the best results in the calibration stage. No outside obstructions were introduced, since a preliminary study showed that the opposite buildings do not cast shadows on the façade of the test room.

As concerns the weather data used for the simulations, the values of the outdoor air temperature measured by the probe were introduced in the weather file available on the Energy Plus website for the city of Catania; on the other hand, the actual global solar irradiance on the horizontal plane was provided by SIAS (Sicilian Informative Agrometeorological Service).

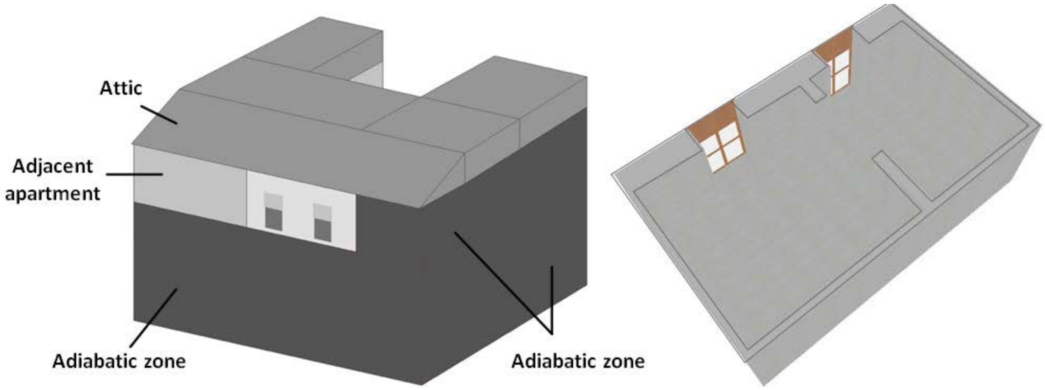

Fig. 3. Model of the building for dynamic simulations. Left: whole building. Right: detail of the test room

4. Results and discussion

4.1. Experimental results and model validation

The experimental campaign, carried out according to the method0ology described in Section 3, has allowed to describe the thermal performance of the traditional wall made of massive basalt stones.

First of all, Fig. 4 shows the outdoor forcing conditions during a representative week in July (air temperature, solar irradiance impinging on the outer surface of the wall). This was a sunny and hot week, with daily peak air temperatures ranging between 32°C and 35°C, while at night the air temperature used to decrease to 25-26°C. The peak solar irradiance on the South wall was around 400 W·m^{-2}.

As concerns the indoor air temperature in the test room, Fig. 5 shows the comparison between the measured values and the values provided by the simulations. Two different rates of infiltration are considered for calibration purposes: the value finally retained (0.25 ACH) provides the results closest to the experimental measurements.

In particular, the simulations are able to follow with good approximation the profile of the measured indoor air temperature, especially from the third day on. Even if the simulations cannot describe some rapid fluctuations of the indoor temperature, the shape of the daily profile is well described, and the maximum discrepancy on the daily peak temperature is below 0.5°C. Apart from the calibration of the model, it is interesting to observe that the indoor temperature shows a daily oscillation with an amplitude lower than 1°C, and keeps steadily above 30°C, meaning that a certain degree of thermal discomfort occurs.

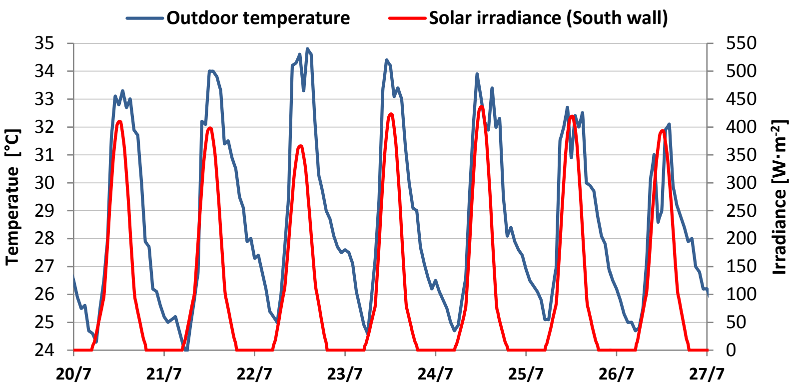

Fig. 4. Outdoor air temperature and solar irradiance on the wall

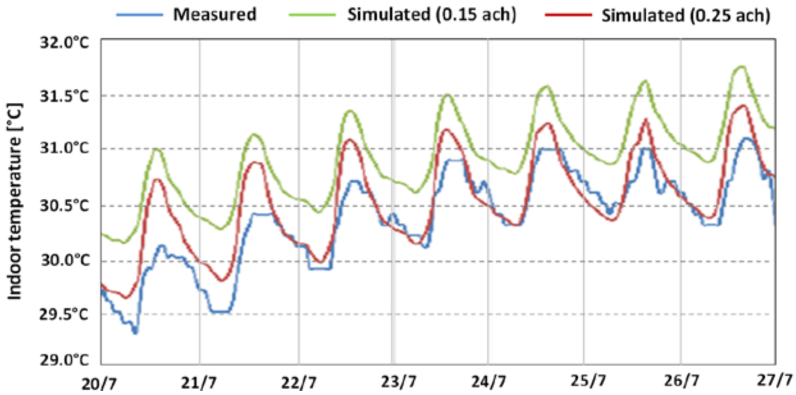

Fig. 5. Comparison between simulated and measured indoor air temperatures

On the other hand, Fig. 6 proposes a comparison between measured and simulated surface temperatures. As concerns the outer surface temperature, a slight discrepancy occurs in the nighttime, maybe due to inaccuracies in the calculation of the radiant heat transfer to the sky. During the sunny hours, the correspondence is satisfying, and the maximum discrepancy on the daily peak temperature is around 1°C. The inner surface temperature keeps almost constant on a daily basis, due to the high thermal inertia of the wall. Throughout the week, a slight and steady increase from 28.5°C to around 30°C is observed in the measured values. The simulations provide higher results, but the discrepancy stabilizes below 1°C.

Moreover, from the analysis of the measured surface temperatures it is possible to infer the values of TL and DF, as defined in Section 3. The results concerning the selected representative week are summarized in Table 2. It is interesting to observe that, in real conditions, both TL and DF assume different values in different days. In particular, TL ranges between 5 and 10 hours, whereas DF varies between 0.01 and 0.02. The experimental value of TL is much lower than the theoretical value determined by UNI 13786 (TL = 18.7 h), while DF approaches with better approximation the theoretical value (DF = 0.02).

Actually, the theoretical values are defined under sinusoidal conditions, with constant internal temperature and without any internal gains, which is far from reality. In practice, only experimental measurements provide reliable information on the real dynamic behaviour of a wall; some studies in the literature have shown that TL and DF may significantly vary with the wall exposure, especially in presence of natural ventilation [11].

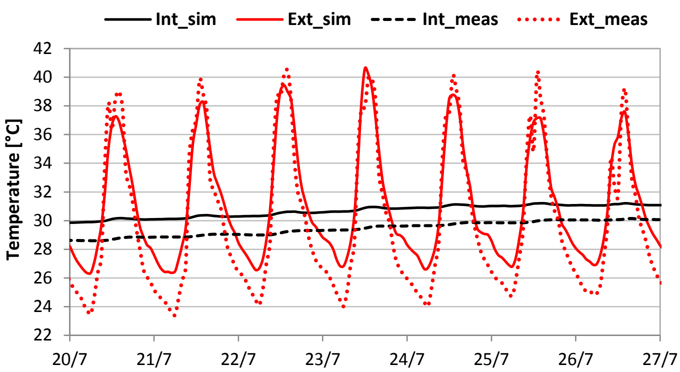

Fig. 6. Comparison between simulated and measured surface temperatures

Table 2. Measured time lag (TL) and decrement factor (DF) for the selected week

Day	20/7	21/7	22/7	23/7	24/7	25/7	26/7
TL [h]	8	8	9	10	6	7	5
DF [-]	0.017	0.013	0.020	0.020	0.015	0.015	0.010

4.2. Modern and traditional envelope: performance comparison

After the validation process, the dynamic simulation model was used to study the performance of the same building but with a modern double-brick envelope (see Table 1). To compare this envelope solution with the actual massive wall under the same U-value, a 2-cm layer of EPS was considered either on the inner or on the outer side of the massive wall. The results of these simulations, in terms of indoor air temperature and wall surface temperatures, are reported respectively in Fig. 7 and Fig. 8 for three representative days (from 27th to 30th July).

As shown in Fig. 7, when applying an outer layer of insulation to the massive wall (basalt stones) the peak indoor air temperature keeps around 0.7°C lower than with a double-brick wall. However, when the insulating layer is applied to the inner side, a pronounced room overheating can be observed. In particular, in this case the peak indoor air temperature attains 32.5°C, that is to say 1.4°C above the peak values observed with an outer insulation layer. A higher daily temperature fluctuation can also be observed. In fact, the inner layer of insulation hides the thermal mass, and prevents it from storing the heat available inside the room, which consequently induces room overheating. Hence, the thermal capacity of the massive wall is not exploited effectively.

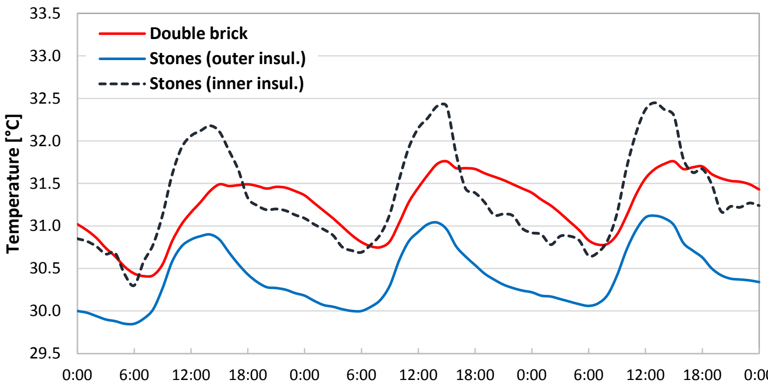

Fig. 7. Indoor air temperature: comparison between modern and traditional envelope (27th to 30th of July)

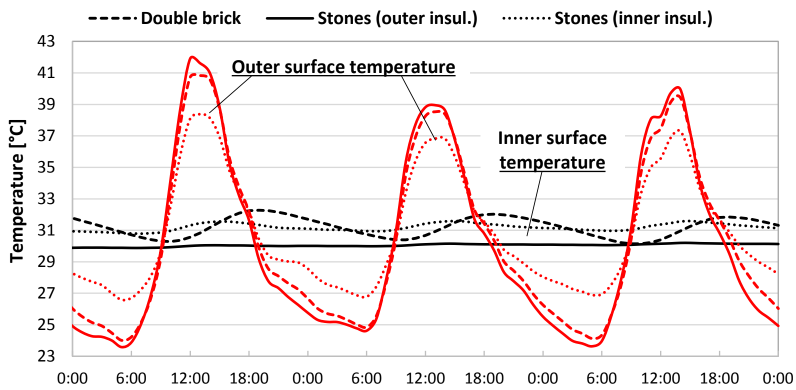

Fig. 8. Inner and outer surface temperature: comparison between modern and traditional envelope (27th to 30th of July)

Similar effects can also be noticed if looking to the surface temperatures. Indeed, the inner surface temperature of the massive wall keeps almost constant (slightly above 30°C) when the insulation layer is placed on the outer side, but it raises by more than 1°C when the insulation is on the inner side, while also showing a non-negligible fluctuation (Fig. 8). In this case, the values of DF and TL are also affected; in particular, TL = 3 h with inner insulation, while TL = 11 h with outer insulation. The double-brick wall has TL = 7 h.

On the other hand, the inner insulation induces the lowest peak outer surface temperature: in this case, the solar radiation absorbed by the outer plaster can be effectively accumulated in the wall, thus reducing the surface overheating by around 3-4°C.

4.3. The effectiveness of nighttime natural ventilation

As discussed in Section 3, a second series of simulations allowed investigating the effectiveness of nighttime ventilation as a means to improve indoor thermal comfort. To this aim, in the simulations the 50% of the glazed surface in the test room was kept open from 00:00 to 06:00. The corresponding results in terms of indoor air temperature and wall surface temperatures are reported respectively in Fig. 9 and Fig. 10.

First, by comparing Fig. 9 with Fig. 7, it is possible to notice that the exploitation of nighttime ventilation provides a significant contribution to decrease the indoor air temperature. Indeed, starting from 00:00, for all envelope solutions the indoor air temperature converges to the same value, i.e. between 27°C and 27.5°C, attained at 06:00. Then, the indoor air temperature shows a sudden rise, mainly due to the heat released by the internal surface of the walls, and keeps increasing until a peak value is reached at the beginning of the afternoon, i.e. between 14:00 and 15:00 (see Fig. 9)

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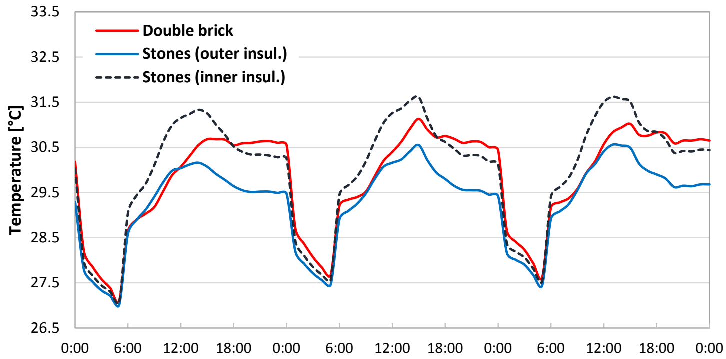

Fig. 9. Indoor air temperature: modern vs traditional envelope with nighttime ventilation (27^{th} to 30^{th} of July)

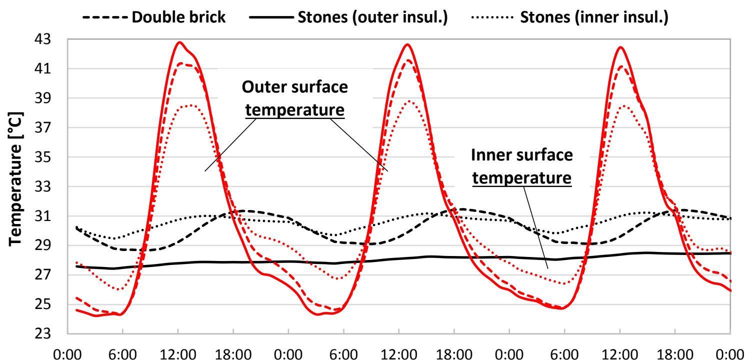

Fig. 10. Inner and outer surface temperature: modern vs traditional envelope with nighttime ventilation (27^{th} to 30^{th} of July)

However, the peak indoor air temperature is significantly lower than in the simulations without nighttime ventilation (Fig. 7): in all cases, this difference keeps around 0.6-0.8°C.

Moreover, nighttime ventilation also plays an important role in decreasing the indoor surface temperature of the outside wall, which would introduce further benefits in terms of thermal comfort. When the massive wall is insulated from the outer side, the inner surface temperature shows slight fluctuations between 28°C and 28.5°C (Fig. 10), which means 2°C below the case without nighttime ventilation (Fig. 8). The other two envelope solutions (double-brick wall, massive basalt wall with inner insulation) have a similar behaviour, even if the massive wall still shows lower temperature fluctuations, and a lower time shift. However, in both cases the peak inner surface temperature is just slightly above 31°C (Fig. 10), whereas in absence of nighttime ventilation this would raise above 32 °C. No significant changes are observed in the outer surface temperature. The main results from all the simulations, in terms of indoor air temperature and surface temperature, are resumed in Table 3.

Table 3. Main results from the simulations: minimum and maximum values for the relevant temperatures

		Indoor air temperature		Inner surface temperature		Outer surface temperature	
		min	max	min	max	min	max
No ventilation	Double-brick	30.4°C	31.8°C	30.0°C	32.3°C	24.5°C	41.7°C
	Basalt (outer ins.)	29.9°C	31.1°C	30.1°C	30.5°C	24.2°C	42.7°C
	Basalt (inner ins.)	30.3°C	32.5°C	30.9°C	31.9°C	26.2°C	38.8°C
Nighttime ventilation	Double-brick	27.1°C	31.1°C	28.7°C	31.5°C	24.4°C	41.6°C
	Basalt (outer ins.)	27.0°C	30.6°C	27.4°C	28.5°C	24.2°C	42.7°C
	Basalt (inner ins.)	27.1°C	31.6°C	29.5°C	31.2°C	26.1°C	38.8°C

Overall, the results shown in this Section suggest that, despite the undeniable benefits introduced by nighttime ventilation, already discussed by the authors with reference to another traditional building in Catania [12], the retrofit solution with inner insulation performs far worse than the case with outer insulation. In fact, nighttime ventilation can effectively remove heat from the inner surface, and makes all solutions comparable at sunrise, as highlighted in Fig. 9. However, as soon as ventilation is interrupted, the role of the wall becomes dominating, and the inner insulation shows all its shortcomings.

5. Conclusions

The experimental campaign discussed in this paper has proven that massive walls with basalt stones, typical of traditional and historic buildings located in Catania (Southern Italy) have a very high thermal inertia. In the summer, this allows to attenuate the indoor surface temperature fluctuation, and to keep it significantly lower than with other more modern envelope solutions, such as double-brick walls. As a consequence, also the indoor air temperature tends to keep below what would be observed with modern envelope solutions, and this difference may also exceed 1°C. This avoids excessive overheating and improves indoor thermal comfort.

However, the simulations have also shown that retrofit solutions of such historic and traditional buildings, based on the installation of insulating materials on the inner side of the walls, may invalidate the thermal capacity of the basalt stones. Indeed, the inner layer of insulation hides the thermal mass, and prevents it from storing the heat available inside the room. Consequently, in this case the room may get overheated, even more than what is observed with a traditional envelope.

Nighttime ventilation can undoubtedly play a positive role in improving indoor thermal comfort, since it helps extracting the heat stored in the walls. However, the performance of the massive walls insulated from inside still keeps unsatisfying. Unfortunately, the retrofit of historic and traditional buildings often must take into account their cultural and aesthetic value, thus the façades cannot be modified. In these cases, the use of insulating materials must be attentively considered: experimental measurement and dynamic simulations may help to point out possible shortcomings.

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