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Efficiency and resilience of temporary housing complexes in L'Aquila 16 years after the earthquake

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Abstract. The housing modules designed after the 2009 L'Aquila earthquake aimed to support the populations affected by the seismic events, with a primary objective of combining safety with energy efficiency aspects. For this reason, the 185 buildings built as part of the "Progetto C.A.S.E." (Complessi Antisismici Sostenibili ed Ecocompatibili), although different from each other, are all oriented towards the pursuit of the same strategic objectives: technological innovation, architectural and construction quality, safety, energy efficiency, and environmental sustainability. The houses, built as part of this project, were initially intended as temporary and provisional structures, but without an expiration date. The aim of the contribution is to verify whether, 16 years after the implementation of the intervention, the houses have maintained their initial characteristics. In this context, the thermal properties of the buildings have been investigated through the infrared thermography (IRT) technique, comparing two different residential typologies. The study revealed that prolonged use of the buildings without adequate maintenance has significantly compromised their thermal performance, resulting in a deterioration of up to 37 % in transmittance.

1. Introduction

The acronym C.A.S.E. was born in the aftermath of Legislative Decree 28 April 2009, n.39, "Urgent interventions in favor of the populations hit by the seismic events in the Abruzzo region in April 2009 and further urgent civil protection interventions". In the text of the decree, in addition to earthquake safety, it is clear that there is attention to aspects of energy efficiency and environmental sustainability, which characterize the entire project concerning production processes, construction materials, rational use of energy sources, heating systems, and building insulation [1]. The housing systems envisaged by the "Progetto C.A.S.E." represent a temporary but long-term housing solution. They were built to meet environmental and structural safety standards similar to those required for permanent buildings, within the constraints of temporary building timelines and costs [1].

The limit between provisional and definitive inspired the content of this contribution, whose aim is to analyze the thermal characteristics of two buildings of the "Progetto C.A.S.E." 16 years after their construction, focusing on the calculation of the transmittance (U-value) of the building envelope.

The method chosen for the experimentation is the IRT technique. Compared to traditional in-situ measurement methods, IRT offers an efficient alternative because it is quick and minimally invasive. [2, 3]. Unlike the heat flux meter (HFM) method, which mainly measures heat flux transfer through conduction [4-7], the IRT method captures both the radiated energy received by the target wall and the heat flux transferred via convection [8]. Albatici and Tonelli [3] assessed the thermal performance of three different in-situ exterior walls to evaluate the practical applicability of the IRT method. Through simultaneous measurements with both the IRT and HFM techniques, they observed that the deviation in IRT results was comparable to that of the internationally standardized HFM measurements, confirming IRT's reliability for field applications. In recent years, several methods have been developed to determine thermal transmittance using infrared thermography, with the choice of equations varying based on whether the measurements are conducted from the building's interior or exterior [9]. Exterior methods, in particular, can be divided into two distinct models: one developed by Albatici and Tonelli [3], and the other by Dall'O' et al. [10]. Both models utilize the same convective heat transfer correlation. Nardi et al. [11] tested both approaches under controlled conditions using a Guarded Hot Box, obtaining similar results for the two cases. Anyway, several studies [12-15], despite recognizing the potential of IRT, emphasize that its data are significantly influenced by boundary conditions, which therefore represent a strong limit for the optimal success of the method. For example, Tejedor et al. [12] showed that the external temperature has a large incidence on the calculations and that IRT is more accurate in heavy multi-leaf walls with high thermal conductivity values. Simões et al. [13] highlighted the need for steady-state conditions for accurate U-value estimations. On the other hand, Nardi et al. [14] demonstrated the importance of a high-temperature difference between the internal and external environment, in addition to stable weather conditions. Finally, Tzifa et al. [15] discussed the uncertainties associated with short-time IRT measurements, noting that relative uncertainties can reach up to 20% under real environmental conditions.

Like the IRT technique, the HFM method is also strongly affected by boundary conditions, which may have a significant influence on the calculations. However, the scientific literature shows that HFM methods generally provide more accurate and consistent results, with average relative errors of 3.3% compared to theoretical values [16]. IRT methods, while faster, exhibit greater variability, with deviations ranging from 6-43% compared to HFM results [17]. This statement is confirmed by the work of Nardi et al. [18], in which the U-values with IRT demonstrated variability compared to those obtained with HFM from 1.69% to 37.28%.

Taking inspiration from the work of Nardi et al. [19], IRT has been tested for quantitative studies on the buildings of the "Progetto C.A.S.E. ". In particular, two different case studies have been taken into consideration. The results obtained were compared with the theoretical transmittance values, previously calculated.

2. Materials and Methods

In this paper, the IRT functionalities have been exploited to analyze with minimal invasiveness the thermal properties of two buildings of the Progetto C.A.S.E. 16 years after the L'Aquila earthquake.

2.1 Methodology

As a first step, to obtain the design U-value of the building envelopes under examination, a theoretical approach was applied. The results obtained theoretically were subsequently used as benchmarks for the experimental analyses conducted with the IRT technique.

3. Case studies

The first building under examination, B1 (Figure 1), is located northeast of Tempera (L'Aquila, Italy), in a rural and hilly context.


(a) (b)

Figure 1. Building B1. (a) Territorial framework. (b) View of the building.

The second building, B2 (Figure 2), is located east of Paganica (L'Aquila, Italy), in a flat rural area.


(a) (b)

Figure 2. Building B2. (a) Territorial framework. (b) View of the building.

The two buildings, even if they are distinct for the individual layers that make up the walls, can be traced back to the same construction typology, i.e., prefabricated reinforced concrete frame structure. The aforementioned technology, being the most common, can be considered representative of the majority of the dwellings built. Tables 1 and 2 show the various layers of the building envelopes with their thermal properties.

Table 1. Thermal characteristics of the B1 building envelope from the internal to the external layer.

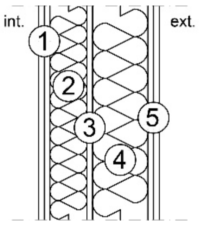
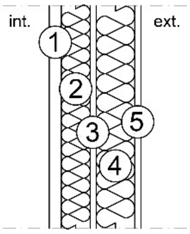
Building envelope	Layer	Thickness (m)	Conductivity (W/mK)
B1 	1. Plasterboard (double layer)	0.025	0.21
	2. Expanded Polystyrene (EPS) insulation	0.08	0.04
	3. Plasterboard	0.0125	0.21
	4. Mineral wool insulation	0.12	0.045
	5. Concrete slab (double layer)	0.025	0.39

Table 2. Thermal characteristics of the B2 building envelope from the internal to the external layer.

Building envelope	Layer	Thickness (m)	Conductivity (W/mK)
B2 	1. Gypsum board	0.025	0.32
	2. Mineral wool insulation	0.06	0.045
	3. Plasterboard	0.0125	0.21
	4. Mineral wool insulation	0.08	0.045
	5. Reinforced concrete slab	0.0125	0.35

4. Analysis phase

The analyses of the envelopes were carried out via theoretical and experimental approaches.

4.1 Theoretical approach

Starting from the executive drawings [1], the design U-value was obtained theoretically, assuming the one-dimensionality of the heat flow, the stationarity of the process, and the homogeneity of the materials' conductivities.

As a first step, the total wall thermal resistance was calculated by applying Ohm's law, expressed by Equation (1):

$$R_{tot} = R_{s,i} + \sum_{1}^{n} R_{cond,n} + R_{s,e} \quad [\mathrm{m^2K/W}] \tag{1}$$

where :

- $R_{s,i}$ and $R_{s,e}$ are the internal and external surface resistances [m^{2}K/W], equal to 0.13 m^{2}K/W and 0.04 m^{2}K/W respectively, as indicated by EN ISO 6946 standard [20];
- $R_{cond,n}$ is the conductive thermal resistance of each layer [m^{2}K/W].

Knowing the total resistance of the walls, the thermal transmittance was calculated using Equation (2):

$$U = \frac{1}{R_{tot}} \quad [\mathrm{W/m^2K}] \tag{2}$$

4.2 Experimental approach

The Albatici and Tonelli formula [3], expressed below (3), was used to calculate the U-value with the IRT technique.

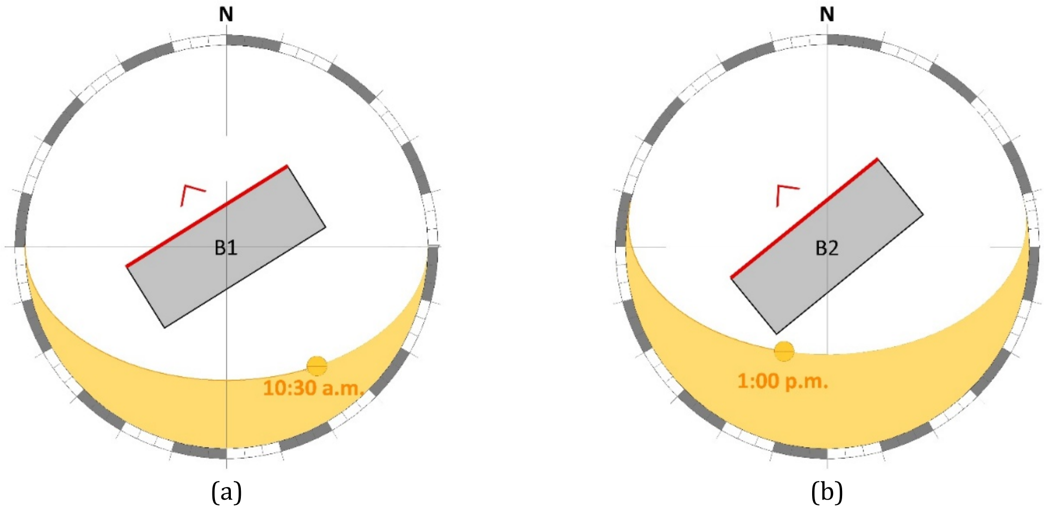
$$U = \frac{\varepsilon\sigma({T_{s,e}}^4 - {T_{air,e}}^4) + 3.8054v(T_{s,e} - T_{air,e})}{T_{air,i} - T_{air,e}} \quad [W/m^2K] \tag{3}$$

Where:

- ε is the surface integral emissivity;
- σ is the Stefan-Boltzmann constant equal to $5.67{\cdot}10^{-8}$ W/m^2K^4;
- $T_{s,e}$ is the external surface temperature;
- $T_{air,e}$ is the external air temperature;
- $T_{air,i}$ is the internal air temperature;
- $3.8054v$ is the convective heat transfer coefficient α_c, with v = external air speed.

The thermographic investigations were carried out in compliance with UNI EN 13187 standard [21], according to which:
- the $T_{air,e}$ must not undergo variations of ± 10°C in the 24 hours preceding the test;
- during the test, the ΔT between the inside and outside of the building envelope must not be less than 10°C;
- during the thermographic survey there must be no significant variations in the $T_{air,i}$ and $T_{air,e}$;
- in the 12 hours preceding the investigation and during it, the areas being investigated must not be irradiated.

The tests were carried out on March 21, 2025, at 10:30 am for building B1, and on April 14, 2025, at 1:00 pm for building B2. The walls examined are those oriented to the northwest, as shown in Figure 3.



(a) (b)

Figure 3. Walls examined with the IRT technique. (a) B1. (b) B2.

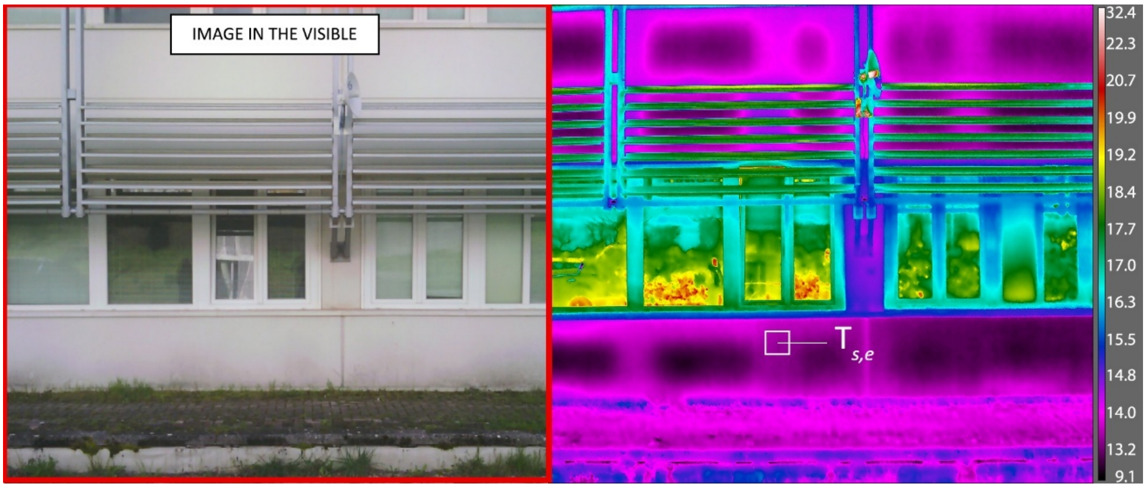
To correctly evaluate the surface temperature (T_s) of the walls, their emissivity (ε) and reflected temperature (T_{ref}) have been measured previously. In our case, emissivity was calculated using the reference method, in accordance with ISO 18434-1 [22]. The aforementioned method involves the comparison of two surfaces at the same temperature, of which the emissivity of at least one of the two is known. For the experimentation, a 3M insulating tape, with an emissivity of 0.95, was used as a reference. As for the calculation of the reflected temperature, it was carried out using the reflector method for B1 and the direct method for B2, following the indications of the ISO 18434-1 standard [22]. The first methodology involves the application of a reflector on the surface under examination. In our case, a crumpled sheet of aluminum foil was used, capable of reflecting in various directions. The second methodology consists of directly framing the part of the environment reflected by the wall. Once the ε and T_{ref} were set, the $T_{s,e}$ was taken by framing a point on the previously selected wall, far from any thermal bridges (Figure 4a).

The calculation of $T_{air,e}$ can be performed using an approximating black body, that is, a device, even a simple one, with a length of 5-6 times its opening [23]. For our test, a black PVC pipe was used. In detail, the measured $T_{air,e}$ represents the average of the temperatures present at the bottom of the tube (Figure 4b).

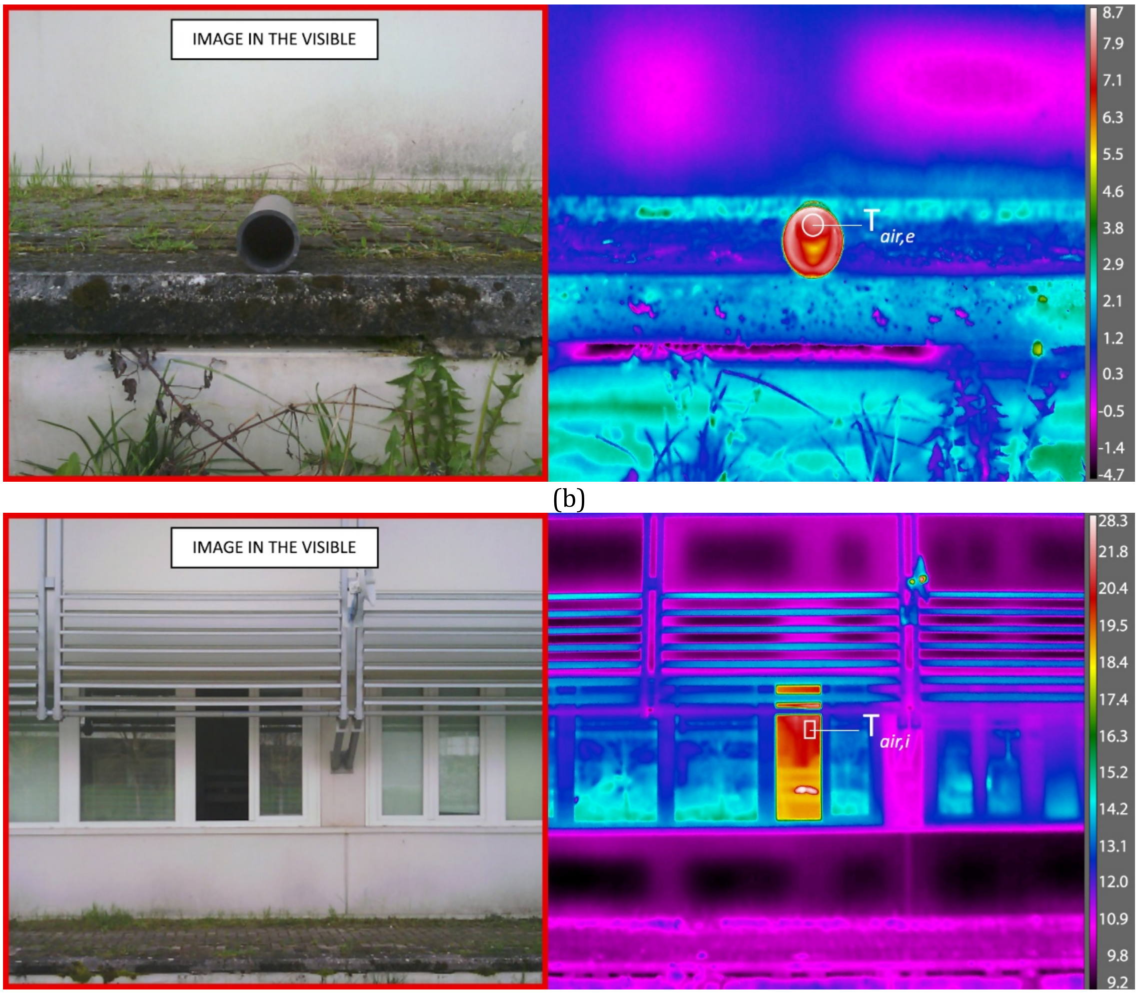
For the measure of $T_{air,i}$, Albatici and Tonelli [3] propose to frame from the outside with an IR camera, the inside of the room during a quick opening of a window (Figure 4c). In this case, the black body is represented by the room, compared to which the partial opening of the window has limited dimensions.

Finally, to measure v, a hot wire anemometer was used.

Figure 4 shows the thermographic acquisition procedure for building B1 (replicated later for building B2).



(a)



(b)

(c)

Figure 4. Thermographic acquisition procedure. (a) $T_{s,e}$ acquisition. (b) $T_{air,e}$ acquisition. (c) $T_{air,i}$ acquisition.

The technical specifications of the measuring instruments used are shown in Table 3.

Table 3. Characteristics of the measuring instruments used for the experimentation.

Sensor	Type	Measuring Range	Accuracy
$T_{s,e}$ $T_{air,e}$ $T_{air,i}$	FLIR T1020	-40 to 2000 °C	• ± 1 C° (5 to 150 °C) • ± 2 °C (up to 1200 °C)
v	LSI Lastem ESV108	0.01 to 20 m/s	• NA (0 to 0.1 m/s) • ± 0.06 m/s (0.1 to 0.4 m/s) • ± 0.08 m/s (0.4 to 3.0 m/s) • ± 0.035 m/s (3.0 to 20 m/s)

5. Results and discussion

The results obtained from the theoretical approach are reported in Table 4.

Table 4. Results of the theoretical analysis.

Case study	$R_{s,i}$ **[m²K/W]**	$\sum_1^n R_{cond,n}$ **[m²K/W]**	$R_{s,e}$ **[m²K/W]**	R_{tot} **[m²K/W]**	**U-value [W/m²K]**
B1	0.13	4.91	0.04	5.08	**0.20**
B2	0.13	3.28	0.04	3.45	**0.29**

The results obtained from the experimental approach are reported in Table 5.

Table 5. Results of the experimental analysis.

Case study	**ε**	T_{ref} **[°C]**	$T_{s,e}$ **[°C]**	$T_{air,e}$ **[°C]**	$T_{air,i}$ **[°C]**	v **[m/s]**	**U-value [W/m²K]**
B1	0.9	11.0	8.4	7.5	20.3	0.01	**0.32**
B2	0.9	5.2	13.3	12.3	23.7	0.01	**0.42**

Table 6 compares the theoretical and experimental results showing their percentage difference.

Table 6. Comparison of theoretical and experimental results.

Case study	**U-value [W/m²K]**		**Percentage of difference**
	Theoretical value	**Experimental value**	
B1	0.20	0.32	37%
B2	0.29	0.42	31%

According to the results obtained, it would seem that, 16 years after the construction of the "Progetto C.A.S.E.", there has been a worsening in the thermal performance of the building envelopes under examination. The aforementioned worsening is evident from the calculation of the transmittance with the IRT technique, which led to results that deviate from the design values by 37% in building B1 and 31% in B2.

6. Conclusions

In the aftermath of the 2009 L'Aquila earthquake, the Italian government implemented the "Progetto C.A.S.E." to provide emergency housing solutions with temporary modular buildings. Over a decade later, concerns have emerged regarding the durability and thermal performance of these structures, initially intended for short-term use. This study presents experimental analyses conducted with the IRT technique on two buildings of the "Progetto CASE", to determine whether the thermal properties of their envelopes have deteriorated over time, compromising internal comfort and energy efficiency. According to the results obtained, it would seem that, although the envelopes of the two buildings were initially compliant with the thermal standards of the time, prolonged usage without adequate maintenance has significantly compromised their performance, resulting in a deterioration of up to 37 % in thermal transmittance. The results underscore the importance of establishing a maintenance protocol for even "temporary" housing solutions, particularly when they become long-term residences. Future developments could involve the comparison of different measurement methods to increase the reliability of the data and the evaluation of the impact of the U-value on the overall energy consumption of buildings.

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