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The energy efficiency challenge for a historical building undergone to seismic and energy refurbishment

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Abstract

The renovation of historical buildings assumes a crucial role in the renovation processes of a historical city, and it is important to foresee appropriate interventions.
A case study in L'Aquila city center is proposed in this work. The building, belonging to listed buildings for its historical value, being built in the 1930s, underwent to seismic and energy refurbishment, since it was damaged by the earthquake of 2009. The solution proposed aimed at improving the energy efficiency of the structure, by using an additional insulating layer, made of natural material (i.e. hemp), on the inside of the wall. The ceilings of the unheated spaces have been insulated, too, by using pure cellulose flocks.
Moreover, an endothermic membrane has been employed on the external walls of the building.
Analyses on the envelope were carried out by using thermographic inspections, performed both in summer and in winter seasons, and by measuring the total thermal transmittance of the wall assembly before and after the refurbishment with the help of a heat flow meter.

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Keywords: Historical building; listed building; seismic and energy refurbishment.

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1. Introduction

The Italian laws in force require high energy performance for new buildings, and for buildings which undergo a refurbishment. This regulation is quite important for Italy, since its building stock is characterized by low quality and energy-efficiency levels.

A separate discussion is reserved for those buildings defined “historic”, that in Italy account for about 30% of the total building stock [1]. For these buildings, in most of the cases, the best available technologies (in terms of technical and economic feasibility) set up for common buildings are not applicable, since they are in contrast with the conservation of their historic value. Most of the technological solutions adopted for the energy renovation of buildings have a high impact on the real estate architecture, which should be preserved through the renovation intervention of the building.

Due to the noteworthy difficulties, which occur in the integration of the solutions for energy saving in historic buildings, the European Directives, in turn adopted by the Member States, issue waivers to the strict norms which impose minimum energy requirements for buildings.

On one hand, it could be effective to exempt some buildings from the fulfillment of requirements, whose realization could alter the aspect of the estate; on the other hand, the waiver to energy renovation constrains seems in contrast with the appropriate and essential refurbishment of the built environment.

It is worth noting that there is a difference between historic building and listed building.

The historic feature is linked to the time of construction and to the employed technique. The cultural feature is connected to the artistic, historic and archeologic value of the estate; therefore, it is safeguarded by dedicated evaluation procedures.

More precisely, a construction which represents “a material witness having civilization value”, which is recognized in a historic period following the one in which the art-work has been built, is referred as “historical building”.

In this sense, in the European zone the last historic period is assumed to end in 1945, year conventionally assumed as divide between the pre-industrialization and the actual era; therefore, each building built before 1945, according to construction processes and techniques, and using materials belonging to such “pre industrialization” period, can be considered as historical building. Nevertheless, a building built after 1945, but with the abovementioned features can be referred as historical.

A building constitutes a cultural heritage, according to the Italian Decree Law 42/2004 [2] (which is the Cultural Heritage and Landscape Code), when it is characterized by an acknowledged “artistic, historic, archeologic and ethno-anthropological” value. In this case, the building belongs to the “listed buildings” and it is submitted to the Commission for the Architectural and Landscape Heritage, an organism of the Ministry of Cultural Heritage and Activities and Tourism, which has the role to approve any intervention on the estate.

Restrictions imposed by the Commission might be applied even on single parts of the buildings (for example, only on the façade).

It is clear that renovation processes and the refurbishment of historic and listed buildings is a complex matter, and different issues and constrains have to be satisfied [3].

On one side, the need for energy efficiency requires interventions, which are often invasive. On the other side, buildings’ features and characteristics, which constitutes their historic or artistic value, must be preserved. For these reasons, customized solutions for each building are foreseen, in order to carry out the best choice case by case [4].

In any case, a systematic procedure for the energy retrofit can be applied, and it can work on complex of buildings, structures or infrastructures, as proposed in previous work [5].

All the different needs explained before are in the spotlight of the reconstruction processes of historic cities, like in the case of L’Aquila, in the center of Italy, not far from Rome.

The city of L’Aquila was founded in the 13th century, and together with its outskirt was hit in 2009 by a devastating earthquake. Almost the 70% of the buildings (in which lived about 65.000 inhabitants), were seriously damaged, and several of them were listed buildings.

The reconstruction phase of the city and the restoration processes of the buildings are ongoing and are obviously taking into account the energy efficiency requirements.

The challenge for engineers and technicians involved in this huge construction site, defined "the biggest in Europe" [6, 7], is to give back to citizens accommodations which are safe under the seismic point of view, less energy consuming and, possibly, refurbished with sustainable materials.

In this paper, an historic and listed building undergone to energy refurbishment has been studied. An additional insulating layer of hemp has been added on the inside of the wall assembly, while the ceilings of the unheated spaces have been insulated by means of pure cellulose flocks. An endothermic membrane has been employed on the external walls, and the overall thermal transmittance of the envelope after these interventions has been measured with the help on a heat flow meter.

To complete the survey on the building, thermographic inspections have been carried out during winter and summer, in order to identify possible weak points on the envelope.

2. Case study

2.1. Overall description

The refurbished building, object of this work, was built in the 1930s. Due to its historic value, it has been labeled as listed building, together with the others which stand in the immediate nearby and within which it forms a condominium. In Figure 1 an aerial view of the complex contoured by a dotted yellow line is shown, while a solid shape highlights the investigated building.

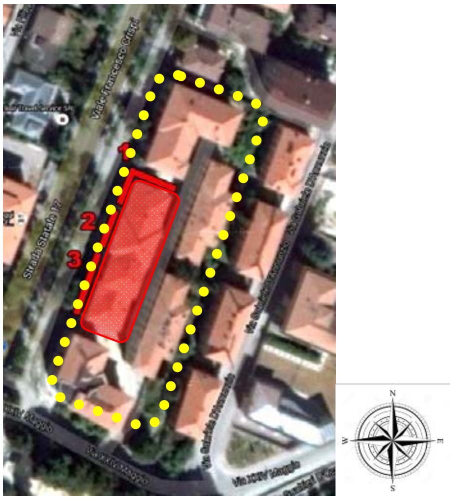


Fig. 1. Aerial view of the investigated building in its urban context. Numbers refer to the viewing point for thermographic inspections.

A particular feature of the walls relies in their thicknesses, which decrease along with the height. Therefore, the external walls of the first floor are thicker than the ones on the third. This peculiarity is shown in Figure 2, where a section of the entire west external wall is drawn. Figure 3 shows the perspective drawing of the west wall, that is the one that faces the main street.

The wall assembly of the first floor is made of cement blocks and masonry; the second and third floor walls are realized with the typical construction technique at that time: masonry walls, made of bricks and stones, that constitute the bearing structure of the building. Sections are detailed in Figure 2, where sizes are expressed in cm.

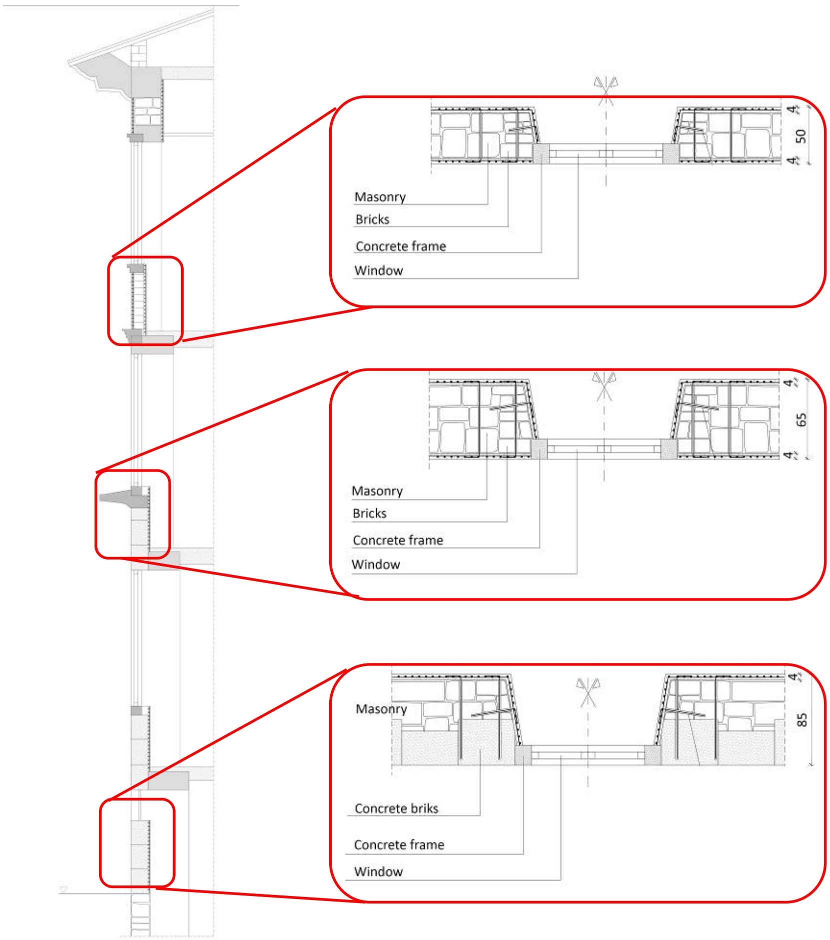


Fig. 2. Section of the west-viewing building wall.

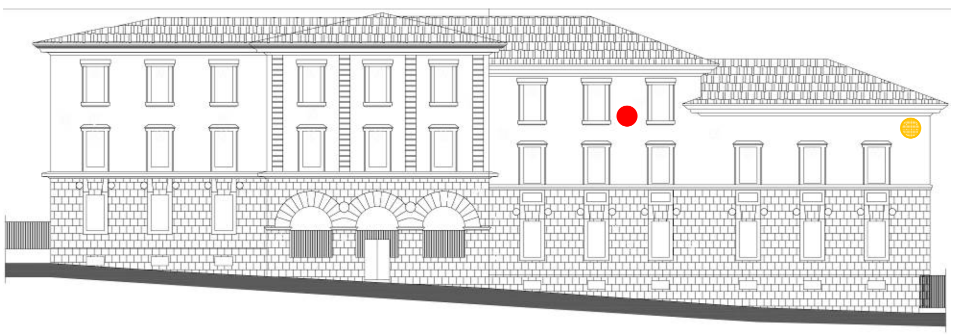


Fig. 3. West view of the inspected building. Dots locate the measurement points.

2.2. The retrofit intervention

The unevenness of the wall assembly of masonry walls is quite common for this building typology. In this case, it is clearly visible in Figure 4-a, that shows the wall and ceiling of a flat after the plaster removal (which was a preliminary work needed for the retrofit intervention). Hemp fiber panels, 8 cm thick for the main walls and 10 cm thick for spandrels, were mounted thanks to frames, as seen in Figure 4-b. The new wall assembly includes a double layer of plasterboard on the inside, and finally cellulose flocks blowing. Figure 4-c shows a workman operating the blowing on the ceiling.

Fig. 4. Progress of the retrofit intervention: (a) wall and ceiling without plaster; (b) hemp fiber panels mounted on steel frames; (c) cellulose flocks blowing on the ceiling.

Natural materials have been chosen according to compatibility and breathability criteria. In fact, an important issue that arises in the case of refurbishment by insulation addition concerns the overall vapor permeability (i.e. the breathability) of the structural elements. In case of improper design and choice of materials, some problems may arise, like moisture (superficial or interstitial) or mould growth. Natural materials provide better characteristics in this sense.

Despite the advantages of the employment of natural materials, some drawbacks must be taken into account, such as the resistance to fire or biological attack. In fact, this kind of materials is often object of insect attack: small animals can feed with these materials, or use them as burrow. To prevent this inconvenience, some chemical treatment or the addition of small percentages of synthetic materials (like polyester) can be foreseen.

The main characteristics of the employed materials, taken from products' datasheets, are detailed in Table 1.

Table 1. Main characteristics of the employed natural materials [8, 9].

	Density	Thermal conductivity	Specific heat	Vapor resistance
	[kg/m^3]	[W/(m K)]	[J/(kg K)]	[ND]
hemp	50	0.038	1700	1-2
cellulose flocks	40-60	0.038	2150	1.2

As external finishing, an endothermic membrane (i.e. a thermoshield) has been employed on the external walls. This coat provides elasticity to the plaster, thus preventing its craquelure.

The main characteristics of the employed thermoshield, taken from technical reports and information provided by the manufacturer, are detailed in Table 2.

Table 2. Main characteristics of the employed thermoshield [10].

Thermal conductivity	IR Emissivity	Solar radiation reflectivity
[W/(mK)]	[ND]	[ND]
0.02-0.04	0.5	> 0.9

These values are comparable to those available in literature [11, 12].

It is clear, however, that characteristics of this kind of barrier depend on the manufacturing (i.e. embedded particles dimension and concentration) and on workmanship anomalies (like, for instance, layer thickness) [11, 13]. To take into account the coating's optical feature, some authors introduce the "effective emissivity", defined as the ratio of the radiative flux exchanged from the treated surface and the one form the surface of the corresponding ideal black body [11].

In Table 3 the final wall assembly of the structural member analyzed in this work (vertical wall) after the refurbishment, is reported.

Table 3. Final wall assembly (after refurbishment).

Layer*	Material	Thickness (d)	Thermal conductivity (λ)	Thermal resistance (d/λ)
		[m]	[W/(m K)]	[(m^2 K)/W]
1	Plasterboard	0.0125	0.210	0.0595
2	Plasterboard	0.0125	0.210	0.0595
3	Vapor barrier	0.005	0.220	0.0227
4	Hemp fiber panel	0.08	0.04	2
5	Plaster	0.04	0.83	0.0482
6	Masonry	0.5	1.009	0.4955
7	Plaster	0.04	0.83	0.0482

*from indoor to outdoor.

3. On-site surveys

The knowledge of the external wall thermal transmittance before the refurbishment was crucial for determining the thickness and type of material needed for a proper thermal insulation.

For this reason, technicians deemed necessary to perform on-site measurements.

Many techniques and methodologies can be employed to obtain the thermal transmittance of a wall [14], which can require destructive or non-destructive testing. In this case, thermal characteristic has been retrieved by means of a heat flow meter. The instrumentation was applied on the west wall, the one that faces the main street, in the point sketched by an orange dot in Figure 3. Unfortunately, source data are not available, therefore they cannot be shown in this work, but result is available, used for the calculation of thickness insulation. In fact, the thermal transmittance of the wall used is 1.4 W/(m^{2}K), a value fitting the one proposed by standard [15].

A second measurement campaign was performed by the authors after the refurbishment. Unfortunately, amongst the apartment that were unheated at the time of the planned measurement campaign, there was the one previously studied. Therefore, a heated flat, neighboring the other, was chosen. The point in which the probes of the heat flow meter were placed is marked by a red dot in Figure 3. Although a coring wasn't carried out, it is reasonable to suppose that the wall thickness in the two selected points is the same.

The campaign was carried out following the recommendations provided in norm [16] concerning the installation of a heat flow meter. A suitable portion of the wall has been chosen, taking into account some physical constrains (i.e., the lack of balconies).

The acquisition lasted 168 hours during winter days, and data on heat flow, superficial wall temperature on the inside and outside were recorded every 10 minutes. Then, data have been processed with the average method. The trends of each quantity, both instantaneous and averaged, are shown in Figure 5.

The final thermal transmittance, obtained with the progressive method, is 0.53 W/(m^{2}K).

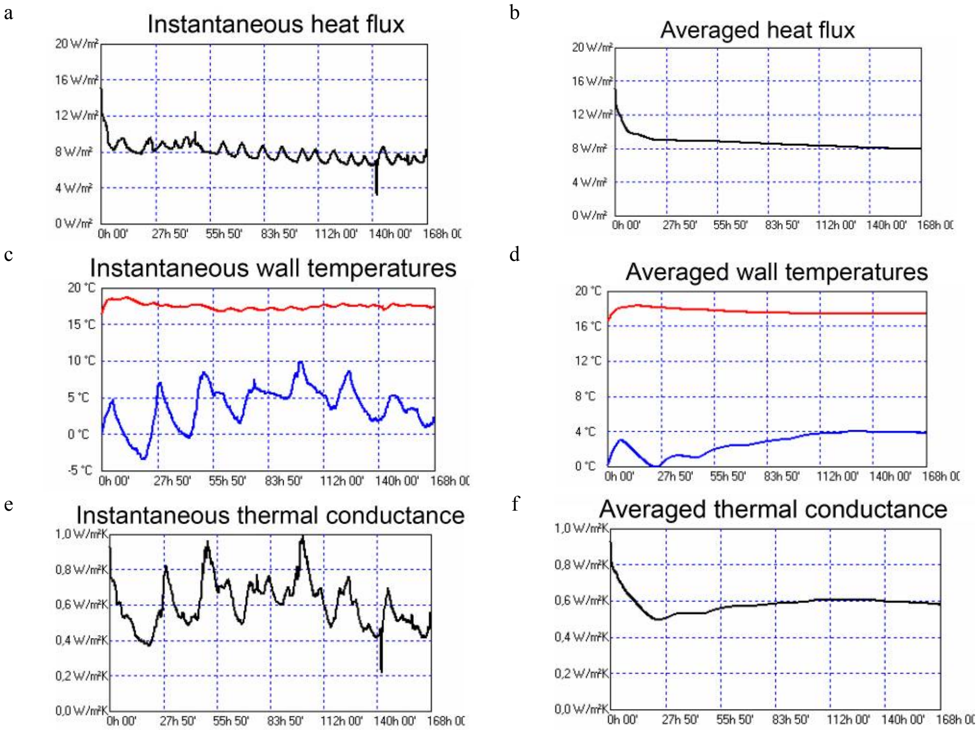


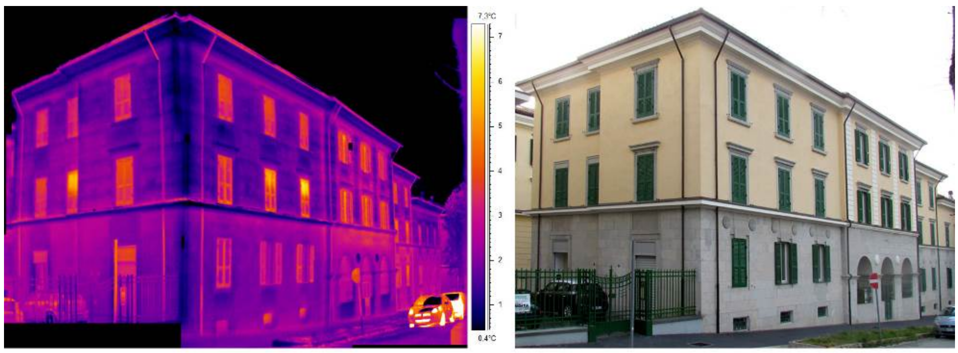
Fig. 5. Instantaneous (on the left) and averaged (on the right) trends of the recorded quantities.

In order to assess if and where there could be heat losses through the envelope of the examined building, thermographic inspections were carried out both in summer and winter. These inspections were also required to preliminarily verify the effectiveness of the thermoshield.

Due to the size of the building, and the presence of trees and traffic signals, it was not possible to take photographs and IR images of the whole west-facing wall. Therefore, multiple acquisitions were needed.

The thermal images taken during the first thermographic inspection, carried out during the winter season, are shown in Figure 6-a and Figure 6-b.

a



b

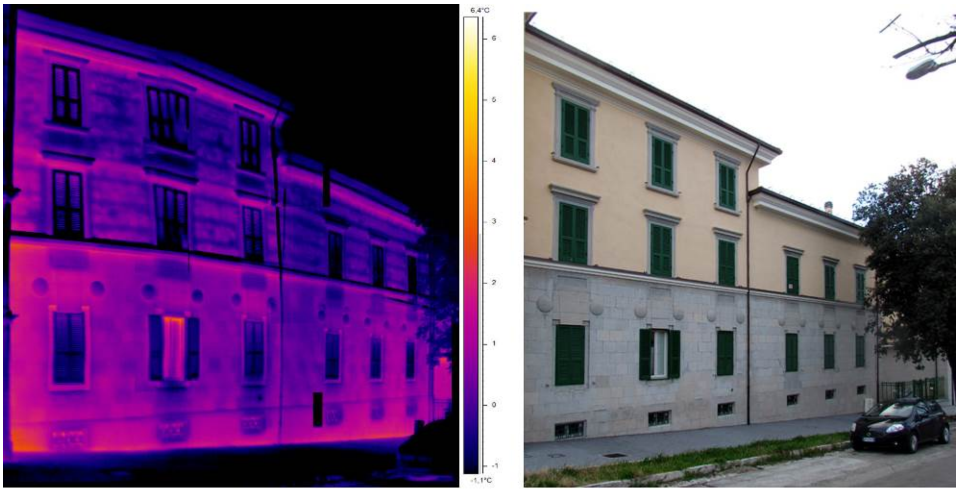


Fig. 6. Images of the investigated building in the IR (on the left) and visible spectra (on the right).

The images show the particular wall texture of the building.

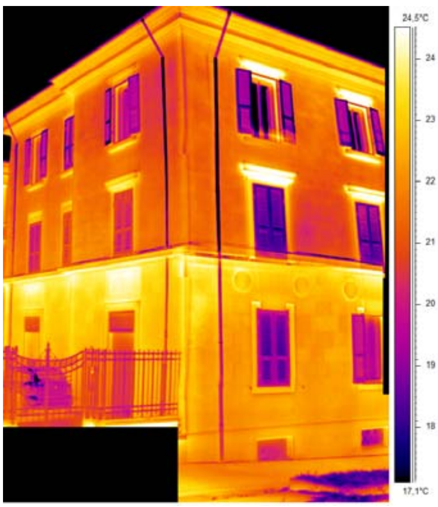
To better visualize details of the envelope, a further inspection was carried out from different points, indicated with numbers from 1 to 3 in Figure 1.

The IR images are shown in Figure 7. Images on the left side are taken in summer, after the sunset, in the phase of thermal discharge of the walls. Images on the right are acquired in winter, avoiding the direct solar radiation on the walls.

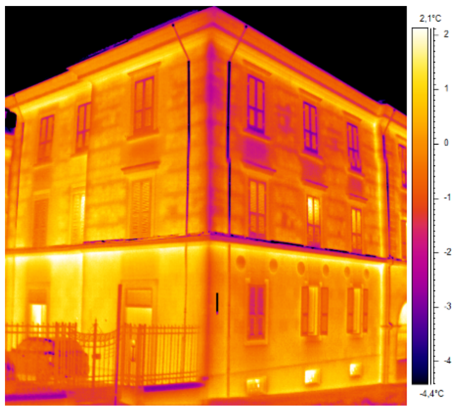
In detail, Figure 7-a and Figure 7-b are taken from the viewing angle indicated as 1 in Figure 1, Figure 7-c and Figure 7-d from the viewing angle 2, and finally Figure 7-e and Figure 7-f from the viewing angle 3.

To better view the thermal anomalies, it is necessary to reduce the temperature scale. This must be taken into account in the following considerations. In fact, in the proposed images it is possible to sketch defects and anomalies thanks to the slight maximum temperature difference that the scales visualize. This implies that anomalies are revealed by colors changes, although the correlated temperatures are slightly different from the ones of the sound areas.

a



b



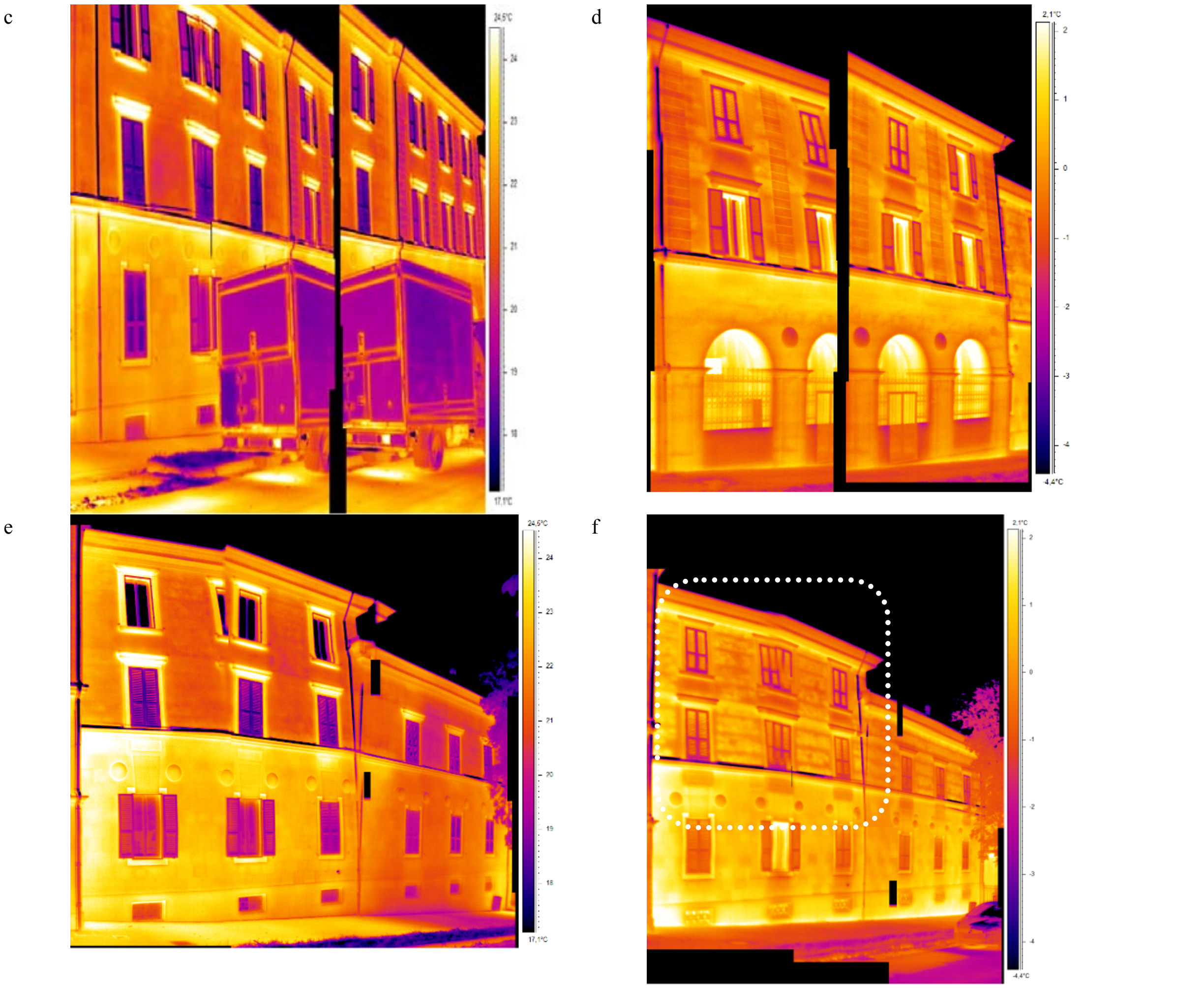


Fig. 7. Thermal images of the building taken in summer (left column) and winter (right column). Viewing angles are those numbered in Fig. 1.

The thermal images clearly show the horizontal layout of bricks in the masonry walls. This arrangement was also documented by photographs taken after the earthquake, as the one of Figure 8 which reproduces the detail of the portion of wall also shown, in the IR spectrum, in Figure 7-f and contoured by a dotted white line.

Another peculiarity revealed by the thermographic inspection concerns the parts of walls which stand below the windows. In fact, since all the spandrels have been insulated with hemp fiber panels thicker than the ones employed for the “regular” vertical walls (since they had thinner wall section, as also shown in Figure 4-b), they reveal a thermal behavior different to rest of the wall.

Fig. 8. Detail of bricks layout on the west wall, third floor.

Finally, a detailed examination of the aspect of the façade has been carried out. The building has been visually inspected, together with the two twin buildings that stand on the East side (visible in Figure 1). These two buildings have been refurbished, too, but without the employment of any particular paint on the external wall. The accurate inspection revealed that the employment of the thermoshield paint on the wall lend more elasticity to the plaster. In fact, there aren't cracks or craquelure on the external wall, despite what retrieved on the twin buildings. Figure 9 shows a detail of such micro-cracks.

a

b

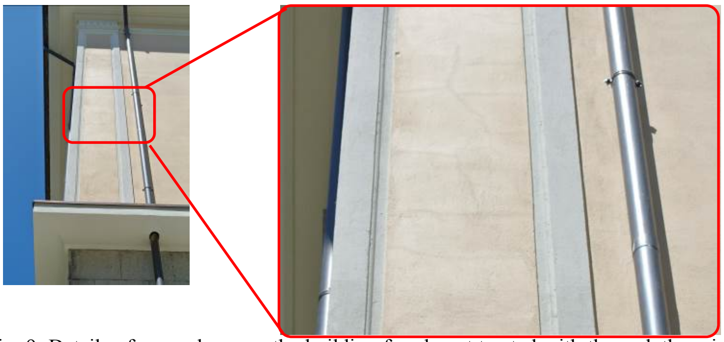


Fig. 9. Details of craquelures on the building façade not treated with the endothermic membrane. (a) near the window; (b) in proximity of a corner.

4. Conclusions

The achievement of energy efficiency targets in the civil sector passes through the renovation of the built environment. Customized solutions, that take into account the specific needs of the structures and their occupants, are foreseen and implemented in the renovation processes which are starting and ongoing all over the world. The attention to materials compatibility and structure breathability, and the avoidance of collateral problems (like for instance condensation, moisture and insect attack) are mandatory for the realization of fine works. Special attention must be paid to historic and listed buildings, for which some constrains are imposed by the supervising organisms in order to preserve their intrinsic value.

This work concerns a listed building that underwent a seismic and energy refurbishment, the latter being carried out with the employment of natural materials.

The paper focuses on the refurbishment of the opaque vertical envelope, realized with the addition of insulating layer from the inside, i.e. by adding hemp fiber panels and two layers of plasterboard. The results show an increase of the thermal performance, which was the purpose of the intervention. Nevertheless, some critical points still remain on the spandrels, as the IR images show.

A feature if the refurbishment of the investigated building is the employment of a coating, specifically an endothermic membrane. The effects of this coating have not been evaluated separately from the effect of the insulation addition. However, it is likely to suppose that this coat displays its major benefits in summer. In fact, based on its high solar reflectivity, the coat can help to lower the absorbed solar radiation. This, in turn, could help to reduce the outside surface temperature swing, which can stress the outside plaster giving rise to cracks. The latter issue is quite critical, since it can raise other important issues for the envelope, like moisture, mold growth, seepages, plaster detachment, and any other damages due to weathering and linked to thermo-mechanical stresses. These concerns lead to an accelerated aging and degradation of the building shell. Cracks formation has been revealed on the plaster of a building, geometrically identical to the investigated one, and standing next to each other, on which the coating has not been applied.

Some other aspects, like the thermal comfort perceived by occupants, will be soon evaluated, even with regard to the flats exposure and to the twin building, which has been refurbished with different systems and materials.

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