Document downloaded from:

http://hdl.handle.net/10251/123537

This paper must be cited as:

Lerma Elvira, C.; Mas Tomas, MDLA.; Gil Benso, E.; Vercher Sanchis, JM.; Torner-Feltrer, MEM. (2018). Quantitative Analysis Procedure for Building Materials in Historic Buildings by Applying Infrared Thermography. Russian Journal of Nondestructive Testing. 54(8):601-609. https://doi.org/10.1134/S1061830918080065

The final publication is available at

https://doi.org/10.1134/S1061830918080065

Copyright Pleiades Publishing

Additional Information

QUANTITATIVE ANALYSIS PROCEDURE FOR BUILDING MATERIALS IN HISTORIC BUILDINGS BY APPLYING INFRARED THERMOGRAPHY

Carlos Lerma[a], Ángeles Mas[b], Enrique Gil[c], Jose Vercher[d], Mª Eugenia Torner[e]

[a,b,d] PhD Architect. Department of Architectural Constructions, Universitat Politècnica de València, Camino de Vera, 46022 Valencia, Spain

[c,e] PhD Architect. Dept. of Continuous Medium Mechanics and Theory of Structures, Universitat Politècnica de València, Camino de Vera, 46022 Valencia, Spain

Corresponding author: Carlos Lerma.

Tel.: +34963879455.

E-mail: clerma@csa.upv.es

QUANTITATIVE ANALYSIS PROCEDURE FOR BUILDING MATERIALS IN HISTORIC BUILDINGS BY APPLYING INFRARED THERMOGRAPHY

ABSTRACT

Historic buildings have a great cultural and architectural value. It is necessary to analyze their state of conservation, but sometimes it is difficult to perform laboratory tests without damaging this heritage. In the field of architecture, infrared thermography is usually used to provide descriptive information about the surface temperature of building materials. This current research presents a methodology widely applicable to historic buildings. As an example of application, the study is focused in the Seminary-School of Corpus Christi of Valencia (Spain), a very outstanding building from the 16th Century. This research presents an analytical study to be able to differentiate the temperature distribution of all pixels of a thermographic image. Thermal images are a matrix of data and their study helps us in decision-making based on objective data.

KEYWORDS

Infrared thermography, historic building, heritage, building material, nondestructive test, rammed earth wall, stone, brick.

1. INTRODUCTION

Infrared Thermography (IR thermography) is a non-destructive testing technique that performs a superficial analysis using the energy reflected by different materials. However, some anomalies can be change the heat flux, like the presence of faults, inclusions, or moisture (Bauer, 2016). Other criteria such as the color of the material, its porosity, the presence of salts or the angle of vision can be studied (Lerma, 2014b). So far, thermography has been applied successfully to analyze walls' bond, moisture mapping or thermal diffusivity of some materials (Grinzato, 2002). Other applications of the thermography methodology are, for example, image processing by statistical analysis (Madruga, 2010), old buildings monitoring (Grinzato, 2002), active thermography on façades (Ibarra-Castanedo, 2010), thermo-physical aspects of materials (Cañas, 2005), moisture detection in building facades (Lerma, 2011; Binda, 2010), study of masonry structures (Meola, 2007) or the specific study of timber (Posta, 2015).

This study focuses on extracting more information about thermal images by image processing, in order to identify and analyze quantitatively the materials of buildings façades. This approach entails a methodology that can be applied for any historical building.

We have applied this methodology to a unique historic building in Valencia (Spain): the Seminary-School of Corpus Christi. This religious institution was built between 1586 and 1610, with the intention of training priests, which still remains as its main function nowadays. Surprisingly, the façades of this building have never been restored or rehabilitated. Its current state has an enormous interest from an architectural, structural or building process point of view. The exterior walls of the building are supported on a perimeter plinth of stone. These walls are made of rammed earth with solid brick inside, according to the practice in Valencia at that time. The building façades are finished with seen brick in some representative points as the bell tower or the upper arches located in the gallery.

2. EXPERIMENTAL

A FLIR B335 camera has been used in this study with a FOL10 wide-angle lens to extend the field of view. The camera has a wide range of temperature from -20 ºC to +120 ºC with less than 50 mK NETD of temperature sensibility.

All infrared images were obtained in two phases on the same day in April, always following the European Standard indications (EN 13187:1998). The first phase was after noon, from 12:51 to 13:25 hours, while the second phase was from 20:33 to 21:24 h, at the sunset. This is because thermal camera results are more accurate (Cañas, 2005) in these specific phases. It is necessary to study the boundary conditions of the building, for example what are the maximum and minimum temperatures of the day.

3. RESULTS AND DISCUSSION

3.1. Comparing images

First of all, we need to compare two thermal images. We will discuss it. The idea is to supplement the information of the standard picture with the temperature observed in the thermal image when we compare them. The main area of a façade is formed by several materials, for example, stone on the right and rammed earth on the left. It is possible to combine the visual state of the materials and their temperature provided by thermography comparing both images simultaneously.

3.2 Multitemporal analysis

Thermal imaging can give us more information about the surfaces and materials object of study. To observe the temperature difference of the analyzed materials as time goes by, several images must be taken in the same day.

Furthermore, it is possible to find alterations in a façade when we compare thermal images at different times of the day. For instance, these alterations can be a spalling zone, replacements or wet areas (Lerma, 2011).

One of the advantages of thermographic technology is to take pictures of non-accessible areas of buildings. The west façade of the Seminary-School is shown in Fig. 1. This west façade has been divided to show the day thermal image (13:06 h) on the right part and the night one (20:52 h) on the left part.

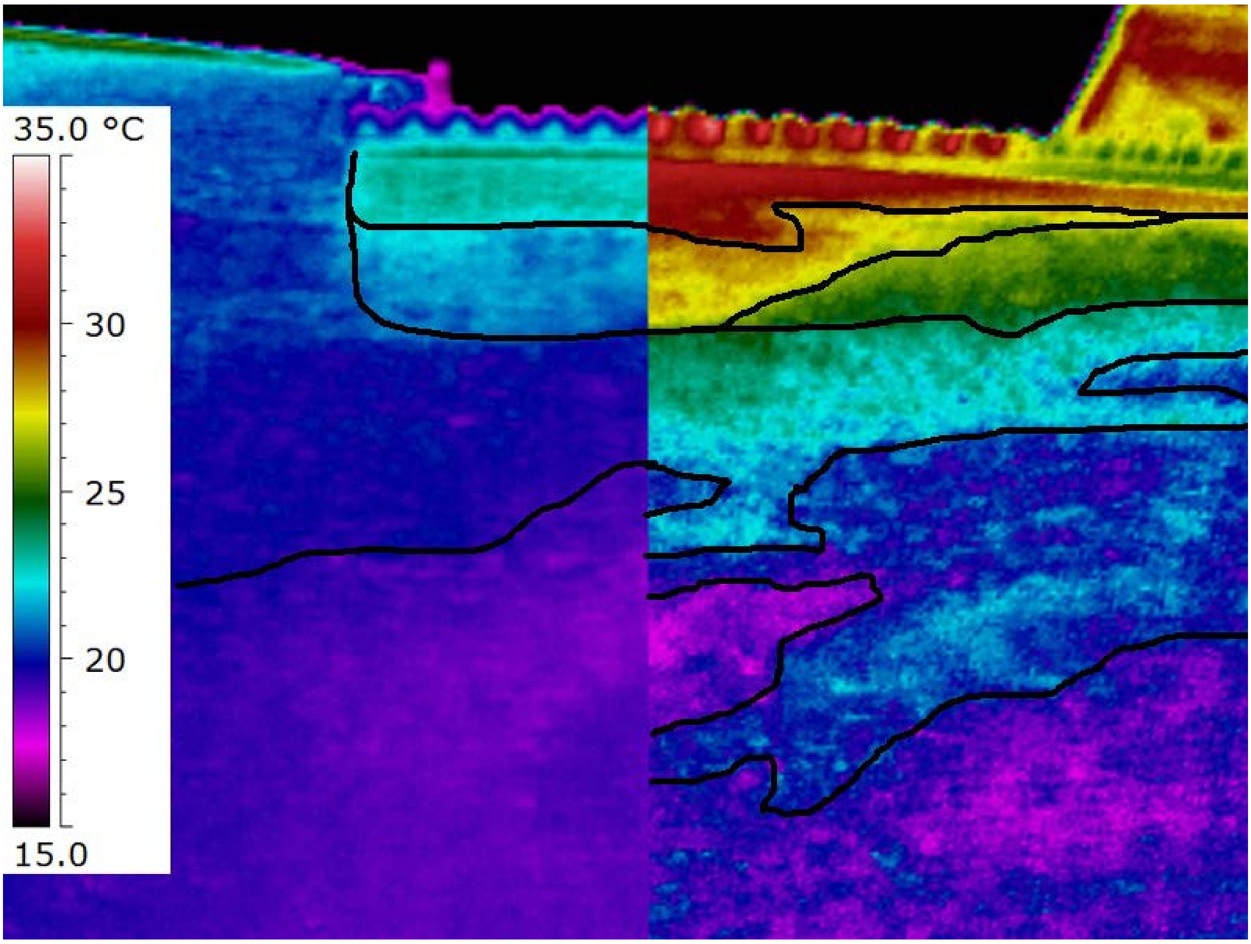

Figure 1. Day (right) and night (left) thermography of the west façade.

There is a clearly different area near the roof where the temperature is higher during day and night in Fig. 1. It is possible that the material of the façade can influence its temperature during the day, but these differences are minimal at night (Barreira, 2007).

After all night, building materials of a façade should have cooled homogeneously because the temperature is the same everywhere, either in the base or near the roof of the building. Some defects can be observed depending on several factors like its geometry (diameter and thickness), its depth or thermal characteristics of the material (thermal conductivity, effusivity). It is interesting to compare the zone with a defect with the surrounding material (Carlomagno, 2011). A warmer area was found where temperature changes are slower. This indicates that the warmer area is located in a wet area with a significant water content (Lerma, 2014b) because it offers an important resistance to heat flow that goes through the wall (Cerdeira, 2011). The energy required to raise the temperature on this wet area is greater than in other zones where there is no water and depends directly on the specific heat capacity of the material (Avdelidis, 2003). Evaporation and drying occurs at the edges of the above area leaving a visible mark on the wall (Válek, 2010).

3.3. Analysis of the temperature distribution

An analysis of each point or pixel of the images has been conducted and therefore we have obtained, quantitatively, the set of points with the same temperature. This analysis is represented in a graph (Fig. 2) where the horizontal axis shows the temperature and the vertical axis shows the number of pixels in the picture that belong to each temperature, in percentage terms. Thermal images show temperature ranges but not their distribution. This method allows to analyze and quantitatively describe a higher or lower temperature areas.

Fig. 2 shows the average temperature (T_a) of all analyzed thermal images, which is 20 ºC. The average temperature has been computed based on the following equation:

$$T_a = T_i * P_i / P_T \qquad \text{(eq. 1)}$$

T_a is the average temperature, T_i is the specific temperature of each pixel *i*, P_i are the number of pixels associated with each temperature value, and P_T are all pixels in the image.

There is a wide range of temperatures on the surface of the main façade of the Seminary-School, as can be seen in Fig. 2. The average temperature and the temperature distribution of the image is obtained by analyzing each pixel, in this case is the average is 20.19 ºC.

A mathematical software has been used to process a large number of images and then calculate the façade temperature. This program shows the intensity value of each pixel in a range from 0 to 255, which can be transformed to a specific value of temperature. This equivalence to a color scale can be shown in a grayscale or in multiple color scale. The temperature range of the image must be known to transform to any color scale, which is obtained applying the following equation:

$$T_i = T_{min} + \frac{(T_{max} - T_{min})}{255} * I; \qquad T_i > 0, I \in (0 - 255) \qquad \text{(eq. 2)}$$

T_i is the specific temperature of each pixel i, T_{min} and T_{max} are the minimum and maximum temperatures measured by the thermal camera and I is the intensity value of the pixel, between 0 and 255.

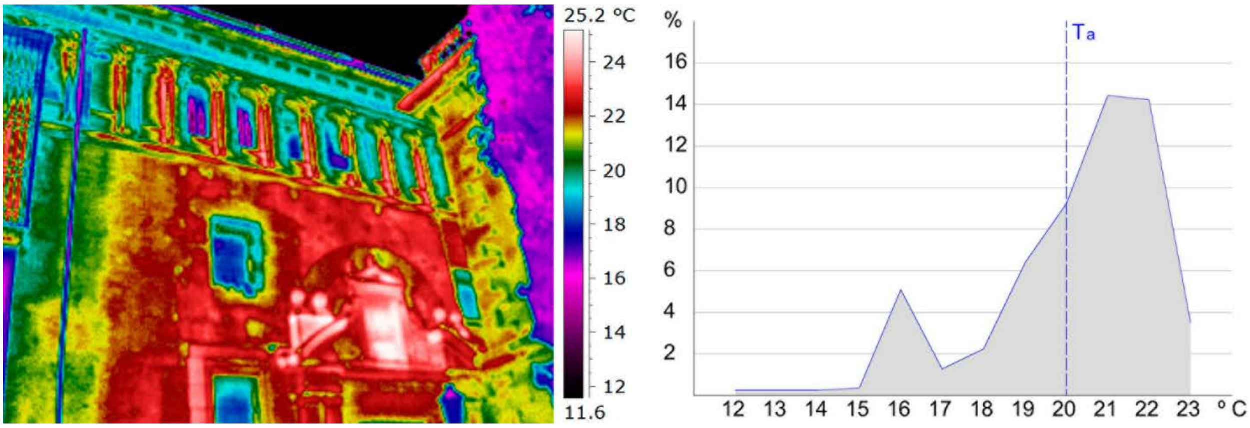

Figure 2. Thermal image evaluation with its temperature distribution.

Sixty-nine images have been analyzed, 30 of them in phase 1 (at 13:00 h) and 39 of them in phase 2 (at 21:00 h). The pixels of the images are grouped based on their associated temperature (Fig. 3). The temperature distribution and the contrasts in this façade of the Seminary-School are higher in phase 1 than in phase 2, because the temperature of materials is located around its average temperature (19.23 ºC).

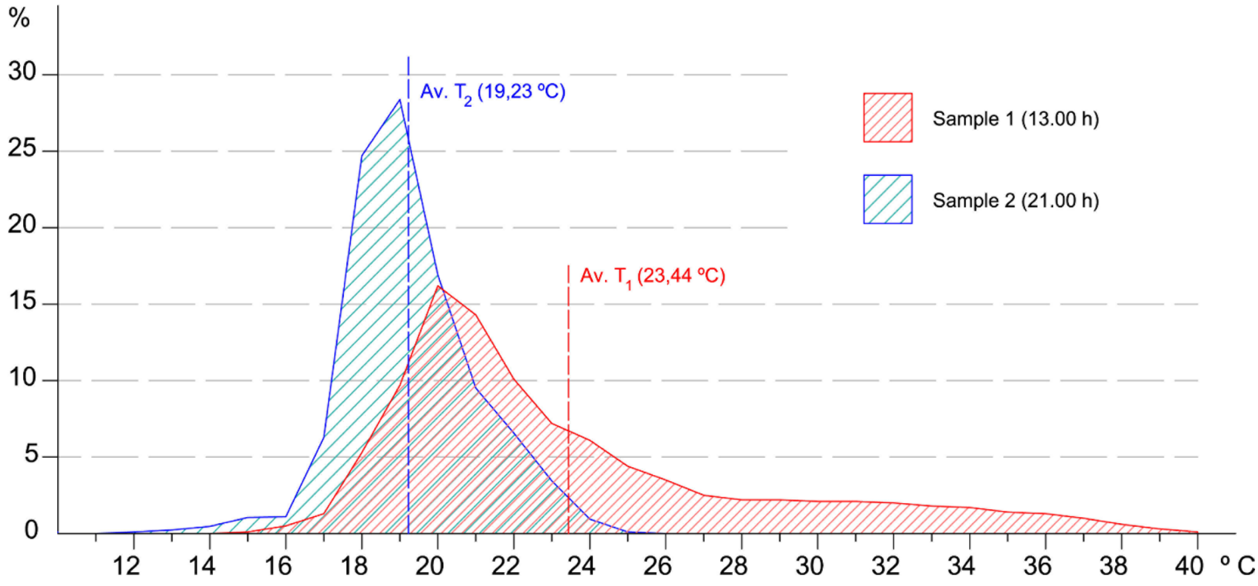

Figure 3. Temperature distribution on the façade of the building.

3.4. Material identification

Infrared thermography can be also used to recognize or identify different materials. Some materials can be easily observed with a direct view while others can be hidden behind a painting, a layer or a cladding of a different material. Moreover, the characteristic texture of the rammed earth wall is identified under the continuous cladding.

Different materials can be observed in Fig. 4: stone, brick and rammed earth wall. At first glance, it is easy to identify the joints of bricks and workstones, which are very marked. However, the position of the joints is more difficult to find out in rammed earth walls because the entire enclosure is coated with a lime mortar. The construction building technique of rammed earth wall was identical to the walls made of lime and mud in Valencia. Bricks are embedded in lime paste in each layer of well compacted earth (Galarza, 1996). Tonality and temperature changes are seen in the thermal image every certain distance, either horizontally or vertically distributed, which allows to identify the joints position. Horizontal timbers were placed in created holes to sustain the formwork. Infrared analysis makes possible to measure the height of different rammed earth courses. Specifically, one rammed earth course is five Valencian spans (1.1138 meters). Fig. 5 shows the position of the rammed earth walls of this zone of the façade.

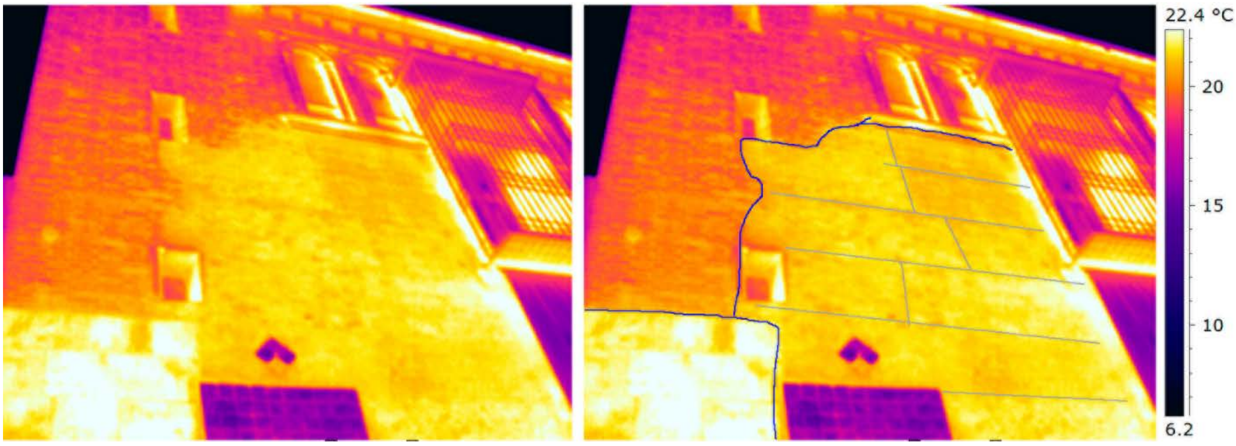

Figure 4. Identification of the façade materials.

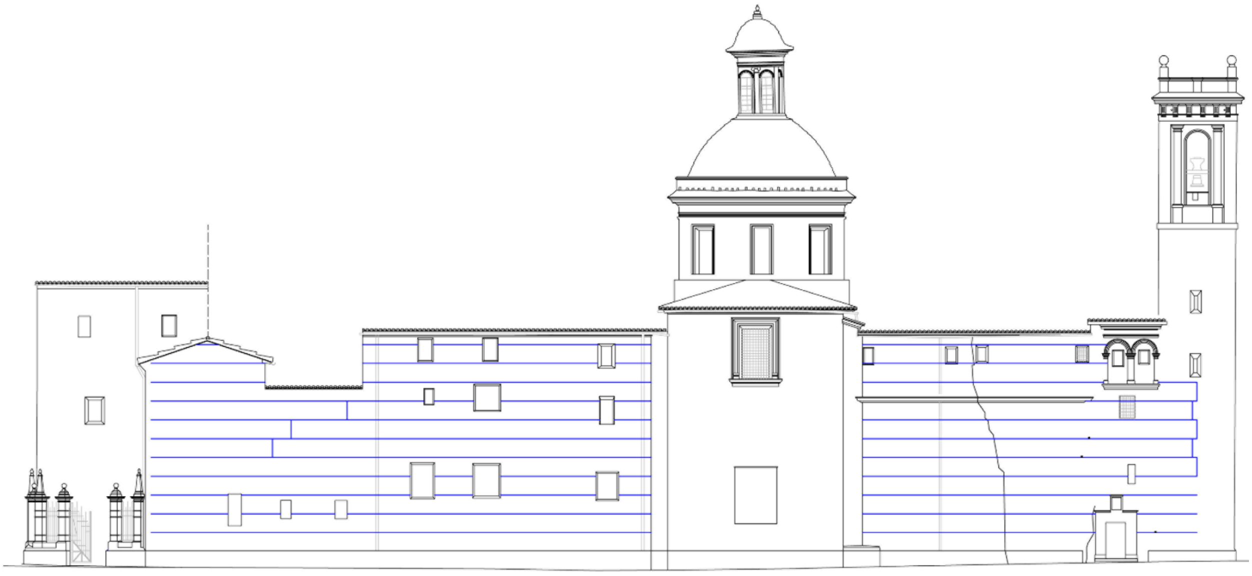

Figure 5. Courses of rammed earth wall in the west façade.

This building walls are 80 cm thick and the information captured in only their surface temperature. In Valencia, a rammed earth wall has a lime cladding all over its surface covering the brick and the rammed earth courses. If there are defects or material changes a few centimeters from the surface, we will observe them using infrared thermography. However, if these defects are deep, we will observe them smaller on the façade surface (Madruga, 2010). The rammed earth wall shows horizontal and parallel lines which are close to one another. In fact, they are precisely the reflection of a discontinuity a few centimeters below the surface. The several stages of the construction process of the wall are reflected by the courses and displayed by these lines in Fig. 5. As it is mentioned above, this non-destructive technique can be applied to distinguish different materials. Two types of stone located on the southwest corner of the building are compared in

Figure 6. Stones up to 2.85 m height show a different color surface with a uniform thermal response. But the workstones between 2.85 m up to 7.65 m show a darker and reddish tonality on their surface. They have a heterogeneous thermal behavior.

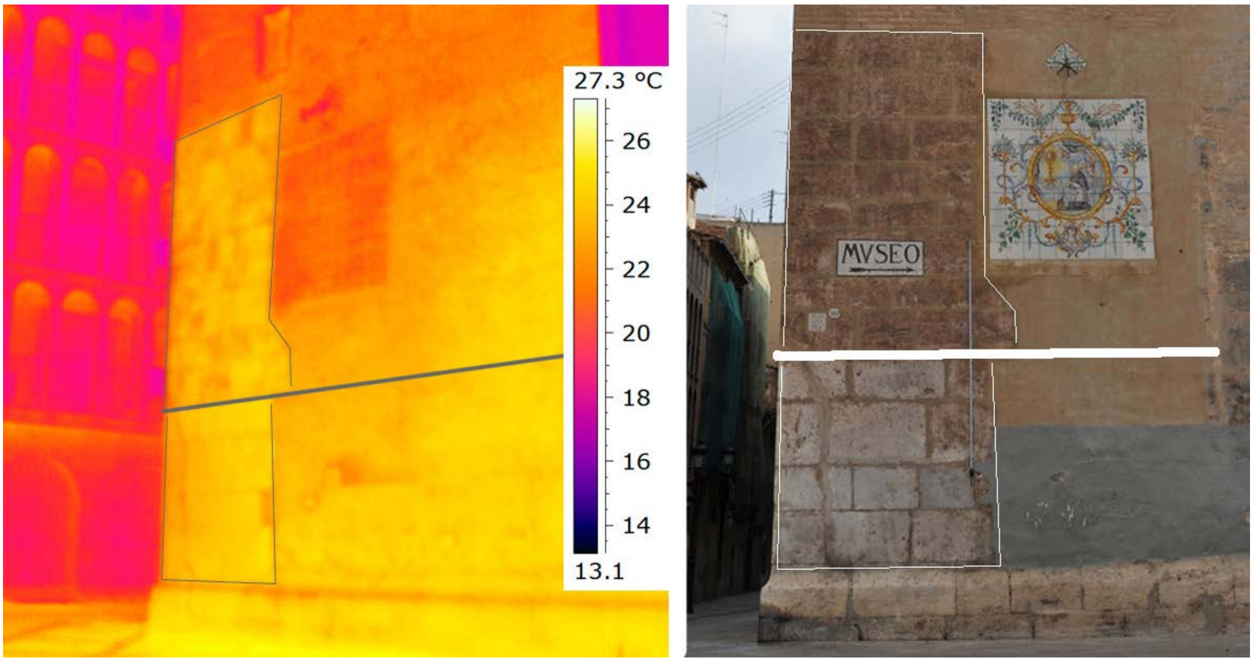

Figure 6. Different thermal behavior of the stone in the southwest corner of the building.

3.5. Analysis of the material

Thermography has been used to analyze the temperature of several materials and their average temperature have been calculated. Specifically, the paper is focused on stonework, seen brick and rammed earth wall. Figure 7 shows the materials that compose this zone of the façade (brick, stone and rammed earth wall, from left to right). It can be shown in Fig. 8.

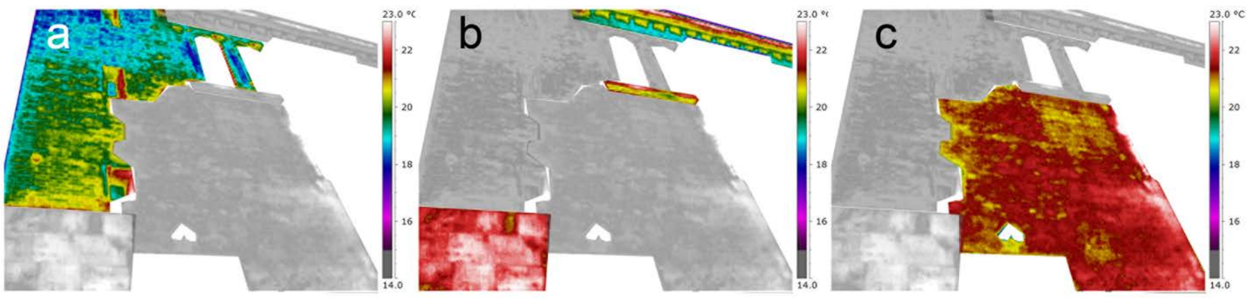

Figure 7. Materials analysis of the façade (a: brick, b: stone and c: rammed earth wall).

Fig. 8 compares the temperature distribution on the same façade on the left graph. The graph on the right shows the average temperature of the previous figures: 19.56 ºC for stone, 20.29 ºC for rammed earth wall and 18.68 ºC for brick. Therefore, in April at 20:30 h, the material that retains a higher temperature after sunset is rammed earth wall, then stone and finally brick.

This rammed earth wall building process has been analyzed and the conclusion is that the same façade was constructed in two phases of the building construction process (Lerma, 2014a).

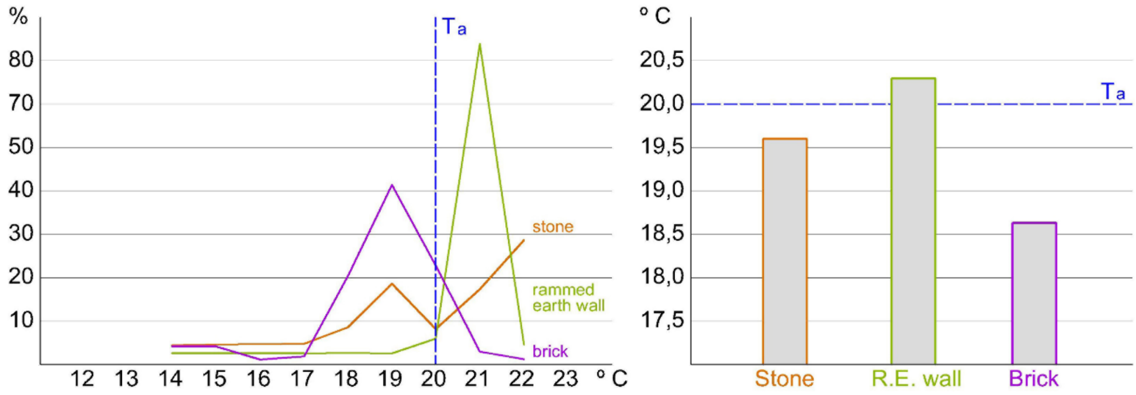

Figure 8. Temperature distribution and average temperature of the façade differentiating between brick, stone and rammed earth.

Fig. 9 show the horizontal and vertical temperature profiles of two specific area of the façade. The graph depicted over the image represents the temperature of each point. Different materials are identified due to the sudden changes in temperature.

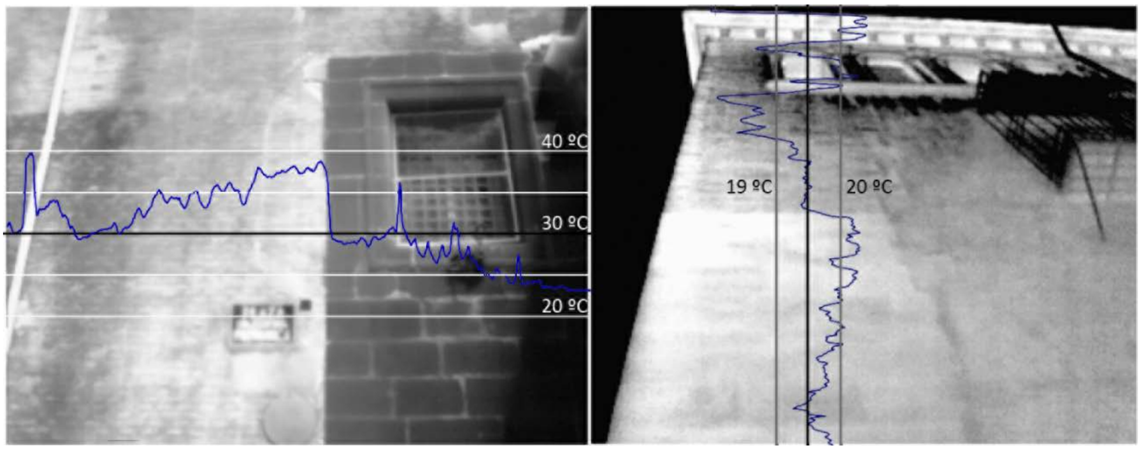

Figure 9. Infrared images and temperature profiles on building façade.

In this case, the studied wall is part of the building west façade. Two thermal images are taken at the same time of the day (20:46 h) under the same temperature (20 ºC) and humidity conditions (40.3%). Each point of the figure is quantified as it is explained above. The graphs in Fig. 10 show the temperature distribution and the average temperatures of both sections of the wall. Obviously, the thermal behavior of these two parts of the same façade is different, although theoretically they are built with the same material. This result supports the hypothesis that the crossing wall of the church is built in another phase of the building construction process.

It is quite interesting to superimpose the elevations prepared by the laser scanning of the building with the thermal images to perform more accurate measurements as it is proposed by Lagüela (2011). However, this building is located in an urban layout surrounded by long and narrow streets. Because of that, thermal images have to be distorted to overlap with the elevations of the building. More information from building materials can be extracted when the sun does not shine on walls, that is, before 8:00 h and after 20:00 h. Thermography analyzes different materials in this building with a study scheduled after many hours of direct and indirect sun exposure. An analysis of each point or pixel of an image has been performed to obtain quantitatively the set of points that have the same temperature. Thermographic images cover a large area of the building façades. and they permit to extract information from each material. Other materials can be compared one another because all conditions are constant: time, temperature and relative humidity. Unfortunately, this is not always possible due to the fact that urban layouts include long and narrow streets. Some precautions must be adopted to compare multiple images, including the setting of the same temperature range.

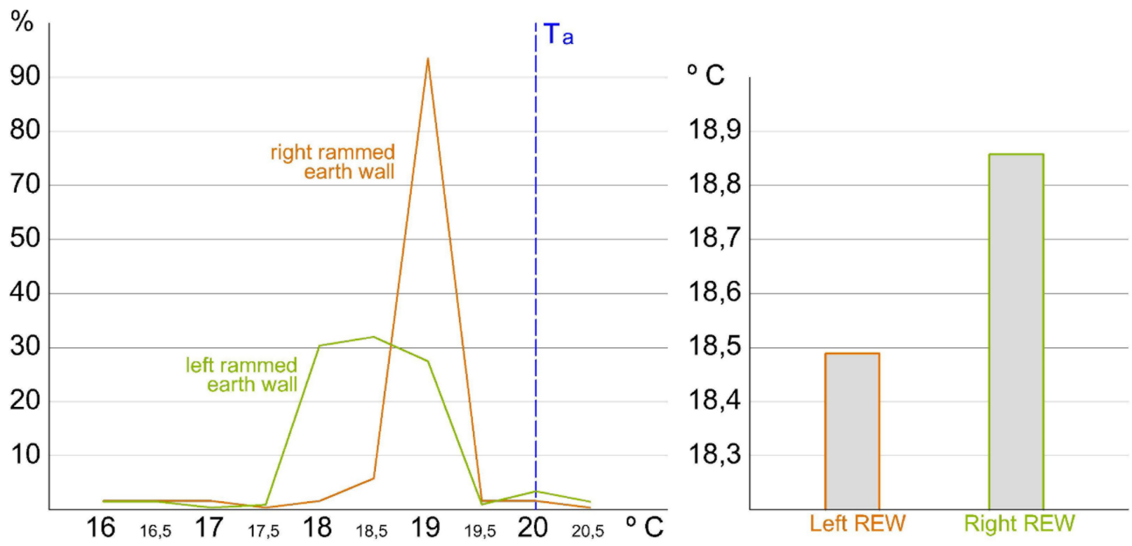

Figure 10: Temperature distribution and average temperatures of the west façade.

4. CONCLUSIONS

Many historic buildings have been built centuries ago, as can be seen in their materials and construction techniques. The interest of analyzing and studying these buildings is undebatable, with the aim of learning from them and keeping them in time in the best possible way. Infrared thermography is one of the main non-destructive techniques to make possible this study.

This research presents a methodology for in-depth study of heritage buildings. As an example of application, this paper was focused on a unique historic building in Valencia (Spain), the Seminary-School of Corpus Christi, which was built over four hundred years ago. This study enhances the knowledge about the materials of this building without damaging it.

The first step in any thermographic study of a building is to compare the thermographic images of the building with the real ones. With this, for example it is possible to detect defects in the façade caused by moisture, due to changes in the expected thermal behavior of the materials. For this reason, the same area has been captured with the thermographic camera during different day and night time periods and the temperature differences observed in the images are compared. Another application is the detection of materials. Infrared thermography allows to quantify the thermal differences between the materials used in a building. Temperature distributions on the building façades have been evaluated to supply additional information about the materials. Sudden changes in temperature are also studied through temperature profiles of the façade to identify different materials. Different building materials have been identified and the area they cover can be known. This improves the knowledge of the materials and helps to analyze the construction techniques used in heritage.

But it is possible to go a step further by the complex processing of the data obtained with thermography. Whereas the simple reading of building surface temperature provides some information, a more appropriate and interesting data can be found through advanced analysis of these data obtained with thermal images. A thermal image can be analyzed as a matrix of temperature values. It is possible to filter, sort or highlight pixels according to different criteria such a temperature values. In this way, thermography can be considered as a rigorous and precise technique. The information extracted from the infrared thermography is usually used in qualitative terms, but with the use of the methodology proposed in this paper, it can show quantitative and more precise information that helps to a greater extent the correct decision making in the conservation process.

5. LIST OF REFERENCES

Avdelidis, N.P., Moropoulou, A. 2004. Applications of infrared thermography for the investigation of historic structures. Journal of Cultural Heritage 5: 119-127. http://dx.doi.org/10.1016/j.culher.2003.07.002

Barreira, E., Freitas, V. 2007. Evaluation of building materials using infrared thermography. Constructiton Building Materials 21: 218-224. http://dx.doi.org/10.1016/j.conbuildmat.2005.06.049

Bauer, E., Pavón, E., Barreira, E., Kraus, E. 2016. Analysis of building façade defects using infrared thermography: Laboratory studies. Journal of Building Engineering 6: 93–104. http://dx.doi.org/10.1016/j.jobe.2016.02.012

Binda, L., Cardani, G., Zanzi, L. 2010. Nondestructive testing evaluation of drying process in flooded full-scale masonry walls. J of Performance of Constructed Facilities: 473-483. http://dx.doi.org/10.1061/(ASCE)CF.1943-5509.0000097

Cañas, I., Martín, S., González, I. 2005. Thermal-physical aspects of materials used for the construction of rural buildings in Soria (Spain). Construct Build Mater 2005; 19: 197-211. Construct Build Mater 19: 197-211. http://dx.doi.org/10.1016/j.conbuildmat.2004.05.016

Carlomagno, GM., Maio, R., Fedi, M., Meola, C. 2011. Integration of infrared thermography and high-frequency electromagnetic methods in archaeological surveys. J. geophys. Eng. 8, S93-S105. http://dx.doi.org/10.1088/1742-2132/8/3/S09

Cerdeira, F., Vázquez, ME, Collado, J. Granada, E. 2011. Applicability of infrared thermography to the study of the behavior of Stone panels as building envelopes. Energy and Buildings 43 1845-1851. http://dx.doi.org/10.1016/j.enbuild.2011.03.029

EN 13187:1998. Thermal performance of buildings. Qualitative detection of thermal irregularities in building envelopes. Infrared method. (ISO 6781:1983 modified).

Galarza Tortajada, M. La tapia valenciana: una técnica constructiva poco conocida. Proceedings of the First National Congress of Construction History. Madrid 1996.

Grinzato, E., Bison, P.G., Marinetti, S. 2002. Monitoring of ancient buildings by the thermal method. J of Cultural Heritage 3: 21-29. http://dx.doi.org/10.1016/S1296-2074(02)01159-7

Ibarra-Castanedo C., Sfarra, S., Ambrosini, D., Paoletti, D., Bendada, A, Maldague, X. 2010. Diagnostics of panel paintings using holographic interferometry and pulsed thermography. Quantitative InfraRed Thermography Journal. Volume 7, Issue 1. http://dx.doi.org/10.3166/qirt.7.85-114

Lagüela, S., J. Martínez, J. Armesto, P. Arias. 2011. Energy efficiency studies through 3D laser scanning and thermographic technologies. Energy and Buildings 43 1216–1221. http://dx.doi.org/10.1016/j.enbuild.2010.12.031

Lerma, C., Mas, Á. Gil, E., Galiana, M. 2014. An analytical procedure for the study of the documented construction process of the Seminary-School of Corpus Christi in Valencia (Spain), Informes de la Construcción, 66 (533), e007. http://dx.doi.org/10.3989/ic.12.117

Lerma, C., Mas, A., Gil, E., Vercher, J., Penalver, MJ. 2014. Pathology of building materials in historic buildings. Relationship between laboratory testing and infrared thermography. Materiales de Construcción, 64 (313), e009. http://dx.doi.org/10.3989/mc.2013.06612

Lerma, J. L., Cabrelles, M., Portalés, C. 2011. Multitemporal thermal analysis to detect moisture on a building façade. Construct Build Mater 2011; 25: 2190-2197. Construction and Building Materials 25: 2190-2197. http://dx.doi.org/10.1016/j.conbuildmat.2010.10.007

Madruga, F. J., Ibarra-Castanedo, C., Conde, O., López-Higuera, JM. Maldague, X. 2010. Infrared thermography processing based on higher-order statistics. NDT&E International 43 661–666. http://dx.doi.org/10.1016/j.ndteint.2010.07.002

Meola C. 2007. Infrared thermography of masonry structures. Infrared Phys Technol 49(3): 228–33. http://dx.doi.org/10.1016/j.infrared.2006.06.010

Posta, J., Dolejs, J. 2015. Non-destructive assessment of timber elements with an emphasis on radiometry. International Journal of Architectural Heritage Volume 9, Issue 6. http://dx.doi.org/10.1080/15583058.2015.1041192

Válek, J., Kruschwitz, S., Wöstmann, J., Kind, T., Valach, J., Köpp, C., and Lesák, J. 2010. Nondestructive investigation of wet building material: Multimethodological approach. J of performance of Constructed Facilities 462-472. http://dx.doi.org/10.1061/(ASCE)CF.1943-5509.0000056