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Feasibility of a Thermography Nondestructive Technique for Determining the Quality of Historical Frescoed Masonries: Applications on the Templar Church of San Bevignate

Vittorio Gusella , Federico Cluni and Riccardo Liberotti *

Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy; vittorio.gusella@unipg.it (V.G.); federico.cluni@unipg.it (F.C.)
* Correspondence: riccardo.liberotti@studenti.unipg.it; Tel.: +39-3387-168-656

Abstract: Thermography is a non-destructive and non-contact technique allowing, without taking samples, gaining information about several aspects of heritage buildings. This contribution presents the last phase of a research path, started with laboratory tests and now aimed at a real case of great cultural value, which involved the use of the thermal imaging camera to unveil in-depth defects and the wall texture, hidden by valuable plasters or frescoes, in order to correlate the quality of the masonry to its mechanical properties. For this, a method has been devised, made of an original integration of thermographic and post-processing techniques, and recently was applied for the first time to a real case study: the Italian Templar church of San Bevignate, part of an architectural complex from the 13th century located in the city of Perugia. The opportunity to establish the masonry quality of a historical building using non-destructive testing (NDT) represents a little-known possibility to frame not only important factors for the conservation of the frescoes but also information on the seismic vulnerability of historical masonry architectures in order to preserve the artefact from being damaged during the surveys and to plan any effective intervention of restoration and structural reinforcement.

Keywords: thermography; fresco; non-destructive evaluation; heritage buildings; historical masonry; seismic vulnerability

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1. Introduction

The conservation of heritage buildings requires critical methodological reflections and careful preliminary analysis, especially with regard to the choice of the strategies of diagnostic investigations and restoration most suitable for the case at hand, in a seamless mediation between architecture, structural engineering, and scientific research. These are the necessary premises in order to assess the seismic vulnerability of historical structures without compromising the role that the architectures had over the centuries and the one they currently play. The historical built needs to be protected through constant monitoring of the "health" of the masonry structures and, in this case, foreseeing interventions based precisely on the data deriving from experimental campaigns focused on deepening the level of knowledge with respect to a building's features. Still to the present day such activities require mainly, and unworthily, traditional destructive testing (DT), e.g., sampling of essays, and rarely are flanked by auxiliary minor-destructive (MDT) and non-destructive (NDT) testing, e.g., metric and/or multispectral surveys, especially in the determination of the masonry texture which is closely linked to the seismic performance of historical masonry structures. Indeed, an adequate knowledge of the actual texture assumes great importance for the estimation, through homogenization techniques, of the mechanical characteristics [1] and collapse conditions [2] of the masonry both in the static and dynamic field [3,4].

Regarding the innovative techniques, these include the use of tools such as laser scanners, digital photogrammetry and thermal cameras which, if applied correctly and adequately integrated with other methods, allow different levels of definition of the state of conservation and of the structural peculiarities keeping the artefacts from damaging during the survey [5–8]. In particular, frescoed walls and decorated vaults, due to the executive techniques and the materials used, cannot be restored if damaged during the investigation phases and moreover suffer from the effects of the deterioration of time (thermal effects, humidity, solar radiation). An ongoing research is carried out by the authors in this field and, among the different techniques available, a particular focus is placed on the aspects related to the application possibilities of the thermal camera. Doing a short premise, it must be pointed out that usually the use of such technology is aimed almost exclusively at damage detection problems, indeed the infrared thermography is well suited for this purpose because it is inherently sensitive to the presence of near-surface defects and can interrogate large areas efficiently. Vice-versa in the previous contributions [9–11] such approach has been enhanced devising a methodology of survey concerning the masonries structural quality assessment, in terms of texture and construction traits hidden out of sight by the presence of plaster or frescoes on the walls in order to correlate the masonry's features to its mechanical properties. Therefore, a procedure was developed, in order to elaborate the thermographic images through post-processing algorithms, that allows obtaining qualitative and quantitative information about wall textures; the validity of such an approach has been verified on plastered wall panels specifically created in laboratory and led to promising results.

In this contribution we present the last phase of such research, addressing the application of the operational and analytical method devised in relation to a real heritage building of great architectural value. As will be described in the following sections, in cooperation with the Municipality of Perugia, the Templar architecture of San Bevignate, a former church from the 13th century, was chosen as a case study since it offers the ideal scenario for such experimental campaign: the church has ancient frescoes on all the internal walls, even at eye level, ideal for performing investigations with the use of a thermal imaging camera; the results of these surveys can eventually be compared with some visible portions of the walls texture emerging from the areas where the original frescoes have been deteriorated/destroyed over the centuries.

2. The Templar Church of San Bevignate

2.1. Historical Background

In the countryside of the city of Perugia stands the Templar architectural complex of San Bevignate. The church, sober and austere in its external appearance (Figure 1), is marked inside by the play of slender ribs and decorated with a pictorial cycle of the mission carried out in the Holy Ground by the Militia Templi, a.k.a. the Templars. Such an exceptional artefact testifies the presence of the order of the temple in Perugia, indeed in 1256 the city's municipality granted the authorization at the Templar diplomat friar Bonvicino to erect the religious building in place of a small church. For the inhabitants of Perugia, and for the Templars, devoting the church to San Bevignate was important considering the popularity of its local mysterious cult back then: traditions tell that he was a hermit monk who lived around 500 AD in the woods of Perugia, the miraculous resurrection of a boy torn to pieces by wolf attacks is attributed to him. There are other recent studies according to which Bevignate might have lived around 1200 AD and took an active part in the order of the Templars [12]. Actually, he was "laically" canonized in 1453 by means of a decree of the Municipality of Perugia (the Congregation of Rites approved the Sanctification only in 1605, despite this they considered him already the first Templars'Saint).

Figure 1. View from outside of the church of San Bevignate.

In 1262 the construction of the church was completed and also that of the Romanesque bell tower with a square plan. The construction of the former monastery, now used as a private residence, corresponds to the same period as well as the octagonal well, still visible today in the garden. In 1312, with the suppression of the Templar Order, the monastery passed to the knights of San Giovanni of Jerusalem and in 1324 Ricco di Corbolo, a merchant of Perugia, bought the complex and established a female monastic community there, likewise placed under the rule of the Order of San Giovanni. In 1517, due to economic problems, the nuns were forced to abandon the monastery which returned to the full possession of the Order of San Giovanni [13]. From that date, the church gradually lost its importance and in 1860, with the suppression of various religious bodies, became the property of the Municipality of Perugia and was de-consecrated. In the last century, it had various uses, a wood storage, a kennel and even a fire station and such peculiar circumstances permitted to preserve, strikingly, the frescoes because they were covered by plaster for decades. After a long and complex intervention plan of consolidation and restoration started following the 1997 earthquake, and in 2009 the monumental complex reopened to the public and the original decorative apparatus was also secured. This was the result of an agreement between the municipality and the superintendence of fine arts of Perugia. In addition, in 2020 another restoration plan concerning the frescoes of the counter-façade and part of the side walls was also completed, with particular attention paid to restoring the original tones of the wall paintings.

2.2. The Architecture of the Church

The church of San Bevignate stands near the ancient route Spargente that was one of the five royal access road axis to the city of Perugia. Such a distinguished monument of Gothic architecture appears as a structure of considerable size made of sandstone and with a double sloping facade decorated with a simple oculus and a single round-arched portal, adorned with a marble frame with symbols typical of the Templars, while another small entrance door crowned with an ogive arch is located on the left wall. At the extremity of the façade two mighty buttresses are clearly visible and recall the others located on the perimeter walls. The building ends with a quadrangular apse interrupted by a mullioned window in travertine. The interior of the single-nave church is divided by two large spans with an ogival cross-vaulted roof and a ribbed cruise that covers the apsidal area, raised above the level of the nave. Perugia has the good fortune to preserve almost intact such testimony, exceptional from an architectural and iconographic point of view. In such phase, the thermographic investigations, gathered in conjunction with digital photographic images, were concentrated on the side wall of the nave facing south since the opposite wall and the apse are partially aggregated within the architectural cluster of the complex of San Bevignate (not the ideal environmental conditions for passive thermal imaging), Figure 2. Furthermore, at the time of the investigations, the entrance wall and other areas were covered by scaffoldings, as the frescoes present there were being restored. Indeed, the church is rich in valuable mural paintings (Figure 3), and it must be said that, among them, the only certainly contemporaneous with the Templar period are actually those of the counter-façade and those above the apse, all the others belong therefore to other Orders. More specifically speaking, the series of the Apostles stands out, distributed on the side walls, superimposed on the original decorations. Concerning the counter-façade above the main entrance is observable an unusual iconographic choice arranged in two registers (one upper and one lower) inherent the efforts of the knights of the temple in defence of the holy sepulchre. Referring to the apse, complex decorative themes are observable portraying Biblical scenes and representations of Templar symbology and of local religious life (e.g., some flagellants can be seen and two effigies of San Bevignate), Figure 4.

In the conclusion of this section, it behoves us to bring up that at the same time as the restoration works following the earthquake occurred in '97, valuable Roman ruins were discovered under the church's floorings. The findings extend for almost the entire width of the nave above and consist in an ancient fullonica characterized by the presence of five basins, the Roman artisan workshop for washing and dyeing fabrics. The fragment of a mosaic with black and white tesserae, on the other hand, is attributable to a previous Roman domus dating back to around the second half of 1st century BC. To date, this archaeological site which also includes the crypt where the Saint was probably buried, apart from the church, is completely open to the public in a single museum itinerary. At the time the thermographic tests were conducted, in the church there were two construction sites in progress and this fact, together with the morphological-architectural features of the church, inevitably restricted the field of investigation. Those construction sites have recently been completed in favour of new ones, so a continuation of the thermographic survey campaign is in process of organization, together with the municipality, for the new year aimed to extend the investigations to all frescoed walls. The resulting new experimental data, which will arise during the survey phase and continue through the detection of different building information, can be very useful to develop appropriate measures for restoration and strengthening of San Bevignate.

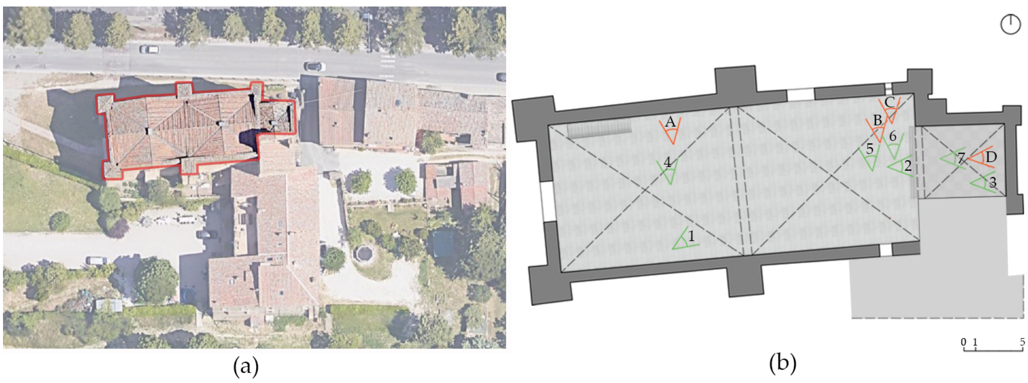


Figure 2. (**a**) Aerial view of the architectural complex of San Bevignate, the border of the church is highlighted in red lines. (**b**) Plan of the Templar church with the photographic cones of vision chosen for the survey: in red the settings of thermographic shootings, in green the digital photography ones.

Figure 3. View of the interior of the church of San Bevignate (see cone of vision 1 in Figure 2).

(a) (b)

Figure 4. (**a**) Pictures of the altar, in background the lower register of the apse'frescoes. (**b**) Detail of the friar Bevignate depicted with a halo as if he were already a Saint and with the white habit consistently with the Templars observable in the counter-façade's mural paintings (see cones of vision 2 and 3 in Figure 2).

3. Principles and Thermographic Data Analysis

3.1. Principles

Remembering that there are three methods of heat transfer (conduction, convection, and radiation) an infrared camera is able to record the amount of radiated heat from an object. In fact, the heat transfer in any material is affected by the presence of subsurface flaws or any other change in material thermal properties. Localized energy differences on the surface of the test object are caused by the changes in heat flow and can be measured using an infrared detector.

The relation between emitted radiation and surface temperature is given by the Stefan–Boltzmann equation

$$E = \varepsilon\sigma T^4 \tag{1}$$

where ε is the radiation (W/m^2), T is the absolute temperature (K), σ is the Stefan–Boltzmann constant (5.67×10^{-8} Wm^{-2}K^{-4}) and ϵ is the emissivity.

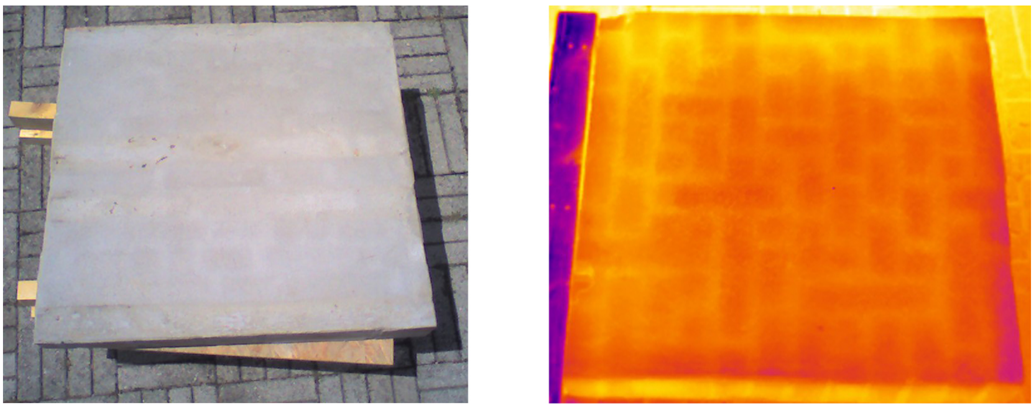
Moreover, the relation between the wavelength of the maximum radiation intensity λ (µm) and the temperature is

$$\lambda = \frac{b}{T} \tag{2}$$

where b is the Wien displacement constant (2897 µmK).

For temperatures close to room temperature, the energy is in the infrared region of the electromagnetic spectrum. In particular, the infrared radiation is the region of the electromagnetic spectrum between visible light and microwaves, containing radiation with wavelengths ranging from 0.75 to 10 µm.

Temperature distributions are obtained by data processing from the measured infrared radiation and then recorded in the form of isotherm plots or thermograms. The electronic sensor of the instrument records the value of energy stored by every single pixel and generate an image, in greyscale represented by black and white shades or in a combination of levels of false colours, of the observed object. An example is shown in Figure 5; it should be noted that the colours of the image are used only to give a representation of the pixels' temperatures.



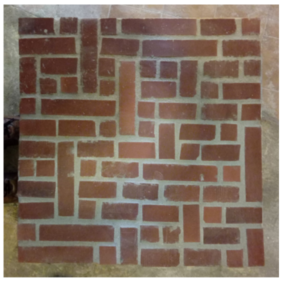
(a) (b)

Figure 5. Preliminary tests of thermographic imaging. (**a**) Quasi-periodic masonry wall sample covered with plaster. (**b**) Its thermographic image.

3.2. Laboratory Validation

To check the capability to assess, by means thermographic images, the texture of masonry wall covered with plaster or frescoes, a research program was started [9–11].

In particular, three masonry samples, which differed for the textures periodic, quasi-periodic, and random, were built. Using UNI bricks of dimensions 250 × 120 × 55 mm, either used as a whole or split in two or four, the periodic texture was built with the running bond scheme and using bricks with the same widths and heights. For the quasi-periodic texture, bricks with different widths but equal heights were used avoiding the correspondence between vertical joints. In the last case, a random texture, made using bricks with different widths and heights, was used. The masonry walls, before applying 10 mm-thick plaster, are shown in Figure 6.



(a) (b) (c)

Figure 6. (**a**) periodic, (**b**) quasi-periodic and (**c**) random.

In that research, as well as for the present paper, the thermographic camera model 885-2 produced by the Testo company has been used. This has a sensor of dimension 320 × 240 pixels. All the samples have been exposed to direct sunlight in order to improve the heat flux through the body.

To obtain the texture from thermographic images, the following procedure was proposed. Temperature data, relating to each thermographic image pixel, can be represented as a scalar field.

$$T_i = T_i(x, y) \quad x = 1, 2, ..., N \quad y = 1, 2, ..., N \tag{3}$$

where N is the image width in pixels, it is assumed that the image has equal width and height.

Assuming a T_t threshold temperature, that field is converted to a binary function, which is a "black and white image" or material binary image, by

$$b_i = b_i(x, y) = \begin{cases} 0 & \text{if } T_i \leq T_t \\ 1 & \text{if } T_i > T_t \end{cases} \tag{4}$$

where the value 1 (black) is associated with mortar pixels, the value 0 (white) with brick/stone pixels.

However, the obtained binary image requires specific treatments in order to improve its quality. At first, mortar (black) region of pixels which are surrounded by brick (white) pixels are removed. Then the use of morphological operators is required. In particular erosion and dilation operator, in this sequence, have to be applied, in order to smooth the contour of the inclusions which otherwise would be very fragmented, due to the noise in the image acquisition phase.

The erosion operator is defined by

$$b_e(x, y) = \text{maximum}\left\{ b(s, t) \text{ for } (s, t) \text{in} N^l_{(x,y)} \right\} \tag{5}$$

and the dilation operator by

$$b_d(x, y) = \text{minimum}\left\{ b_e(s, t) \text{ for } (s, t) \text{in} N^l_{(x,y)} \right\} \tag{6}$$

where $N^l_{(x,y)}$ is a square of side l pixels centred in the pixel at (x, y).

Moreover, it was highlighted that the use of sampling Kantorovich algorithm permits enhancing remarkably the quality of the thermographic images. Furthermore, a sensitivity analysis has been performed considering two sources of uncertainties: the first has been related to the parameters of the morphological operator, the second to the effects of the environmental conditions highlighting the robustness of the proposed procedure.

Applying the proposed procedure, the results shown in Figure 7 were obtained; the comparison with a digital image (see Figure 5) highlights the reliability of the procedure. In fact, the resulting black and white image has a consistent separation of phases, i.e., each stone is surrounded by mortar joints and unrealistic conjunction of inclusions is reduced as much as possible.

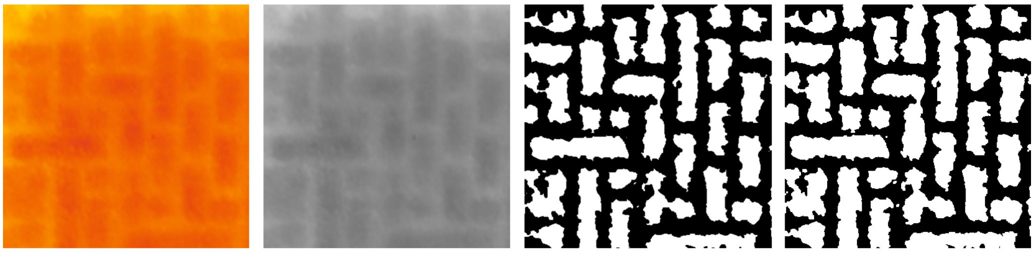


Figure 7. Identified texture of random masonry sample: (**a**) thermographic image, (**b**) surface temperature as greyscale values $T_i(x, y)$, (**c**) black and white image after thresholding $b_i(x, y)$, (**d**) identified texture after erosion and dilation, $b_d(x, y)$.

Nevertheless, these results were obtained in laboratory conditions. In order to check the reliability of the proposed procedure on actual cases and underline the effective importance of this tool in the historical buildings' analysis, it has been started a peculiar study on the Templar architecture of San Bevignate, a former church from the 13th century, whose masonry walls internal facade are covered with famous frescoes.

4. Thermographic Analysis on Frescoed Masonry Walls and Results

4.1. Experimental Campaign

New technologies make it possible to intensify the experimental investigations without harming the architectural quality of buildings, such innovation is exactly fitting with the discipline inherent the heritage architectures [14–17]. Among the important factors influencing the seismic response of Heritage buildings, the masonry quality and the knowledge of its processes of transformation and stratification are certainly included. Therefore, the acquisition of information about the non-visible masonry texture is the subject of such contribution, claiming that the masonry quality is the basic condition to analyse and eventually improve, with reference to the desirable monolithic behaviour, before to insert any reinforcement interventions (e.g., metal tie-rods).

During the present experimental campaign, the measurements were focused mainly on the left side (north) frescoed wall of the nave and the thermographic "shots" were taken under passive conditions: the inner wall's surface was analysed as it appeared at the moment of the investigation, so without heating it, by exploiting direct sunlight and observing the thermal transient that allowed to obtain different responses from the elements with different thermal capacity, in particular by identifying with black pixels the mortar and with the white ones the stone elements.

With regard to the frescoes that decorate the examined wall, rows of overlapping ashlars are reproduced to imitate an austere wall face made of stone, a typical decoration of the Templar churches to recall the poverty of the holy land and of the holy sepulchre. Moreover, the series of the 12 apostles stand out, distributed also on the other side wall, on the façade and the back walls of the apse; such pictorial cycle was superimposed on the original decoration during a second phase between 1283 and 1285. In particular, the first tranche of thermographic investigation covered the mural painting composed by an apostle proceeded by three Saints Maddalena, Stefano e Lorenzo, positioned according to the votive rites required by the ancient order, Figure 8.

Figure 8. One of the frescoes under investigation, in particular the one composed by an apostle proceeded by three Saints Maddalena, Stefano and Lorenzo. In the pic are visible the reflective meter-sticks located as reference points for the subsequent post-processing (see the cone of vision 4 in Figure 2).

4.2. Image Elaboration

Furthermore, dealing with a real architecture, it was necessary to add to the procedure a new phase in order to promote the quality of the final binary image, which is strictly connected to the sharpness of the starting thermographic image. Indeed, compared to what has been described in Section 3, an adjust contrast tool has been used aiming to enhance the black-to-white mapping of the thermographic greyscale image. In visual perception, the contrast is the difference in luminance or colour that makes the elements of an image distinguishable within the same field of view. In the light of all of the above, the thermal images recorded during the surveys were preliminarily modified regulating a good contrast so that the differences between black and white were sharp and the highlights look brighter and the shadows look darker, with intensity values that fill the entire intensity range [0, 255]. Then, the procedure, previously described in Section 3, was applied.

4.3. Identification of Masonry Wall Texture and Peculiar Characteristics of the Frescoes

In the first instance, it was intentional to have an overview of the masonry texture and its quality and then proceed gradually more and more closely to the wall face. Along with the thermographic images "ordinary" digital photos have been taken from similar spots (not the same, as a result of the different focal length); in addition, reference thermal reflective elements have been placed in front of the frescoes, made by two parallel rigid meter-sticks, in order to be able to overlay the photos with the thermographic images in the next phase. Considering that in this first case the meter-sticks were separated by 2.70 m, thanks to the procedure and its final binary images, backed by straightening photographic and measurements digital techniques, it was possible not only to seize the quality of the masonry texture but also its geometry, Figures 9 and 10. A quasi-periodic texture made of bricks with different widths, ranging from 25 to 60 cm, but similar heights, of about 20 cm, is observable; such result matches consistently with what was surveyed in the apse, concerning the areas where the fresco peeled off (see Figure 4). Moreover, the opportunities offered by the thermal imaging methods, regarding at the safeguard of frescoes, mural paintings and valuable architectonic elements, have been addressed by numerous authors with reference different declinations [7,18–22]. Therefore, even if in the present contribution, where the focus was on the identification of the masonry texture, it was anyway possible to contextually ascertain that there are no detachment or infiltration phenomena in place that may endanger the health of the frescoes.

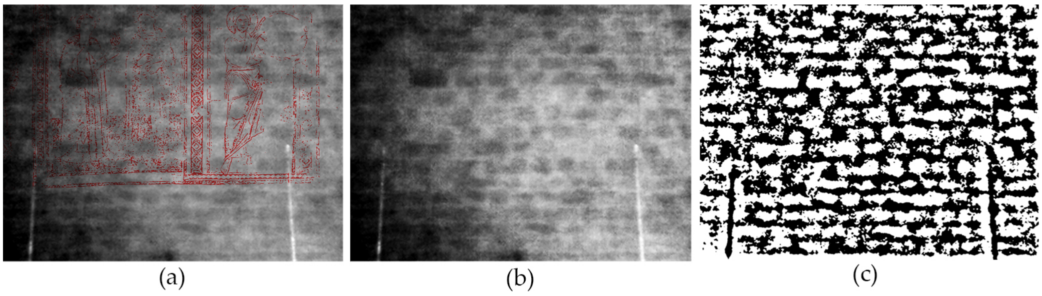


Figure 9. (**a**) Initial thermal image, in red lines is schematized the overlapped fresco. (**b**) Thermal image with improved contrast. (**c**) Final binary image (see the cone of vision A in Figure 2).

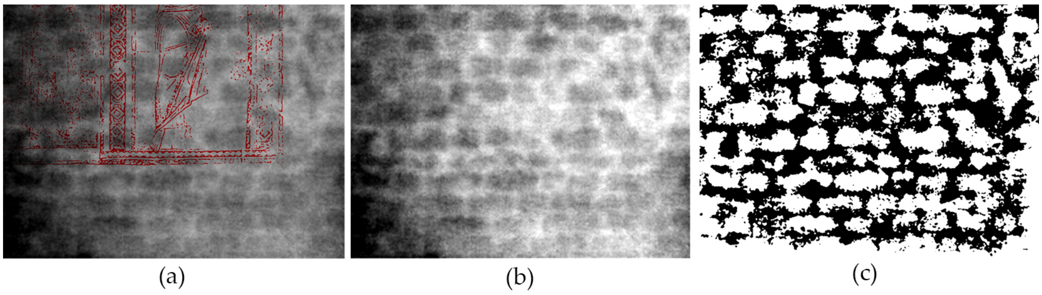
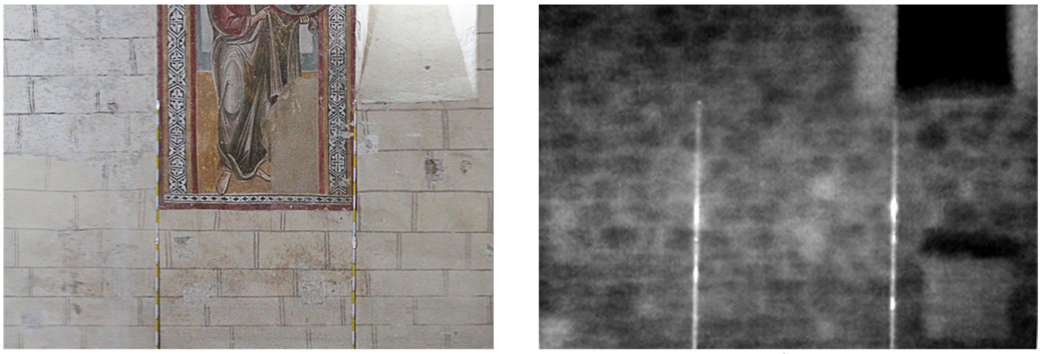


Figure 10. Thermal analysis closer than the previous one to the masonry surface: (**a**) Initial thermal image, in red lines, schematized the overlapped fresco. (**b**) Thermal image with improved contrast. (**c**) Final binary image (see the cone of vision B in Figure 2).

In addition, at a closer look, and in keeping the historical researches from which it has been deduced that the fresco of the Apostle was superimposed to the pre-existing ones, the mortar distribution (in its area) might suggest a trace of the ancient techniques of fresco-makers: the surface of the previous fresco had been probably "excavated" by the masons, allowing the new plaster substance to cling to the ancient mortar below, a less smooth and slippery surface than the wall. Then, the presence of few fragments of mortar out of the joints may show that in order to fasten up the new murals some holes were made by hands in the previous frescoes and therefore their orientation does not follow an exact pattern [19]. This, therefore, testifies that the presented thermographic method, thanks to the possibility of adjusting the parameters described Section 3, is able to provide information, which should be critically evaluated, even about masonries subjected to various superimposed layers of frescoed plaster.

4.4. Identification of Deficiencies and Discontinuities

In such a described approach to thermography, the role of the latter in detection and qualification of deficiencies/discontinuities in the stonework is a significant part [23–26]. Through the analysis of a portion of the same wall, located near the apse and in the vicinity of a window, it was possible to discover the presence of a blind opening in the original masonry, which now is totally bricked up (Figures 11 and 12). In this second case the meter-sticks were placed at a distance of about 1.40 m leading to deduce a size of 65 × 75 cm for the part walled up with a masonry typology different from sandstone, noticing the different emissivity, and the presence of an architrave in another material (probably igneous) of about 15 cm thick. Moreover, on the constructive phases and criteria, the peculiar workmanship, and the different material were still observable on the abutments of the window. Indeed, a toothing masonry has been realized, characterized by the process of leaving alternating openings (teeth) for an adjoining block or brick wall to be started from. Even today, such masonry techniques are sometimes used when windows or door openings must be inserted into an existing wall, by demolition and cutting of masonry, allowing the adjoining wall to be started without having to adjust or cut bricks. It is also interesting to observe how, already with the naked eye (as can be seen in Figures 11 and 12), portions of the fresco with colours of different gradation are observable, probably due to varied breathability of the materials making up the wall. This thesis is also confirmed by what emerged from a closer thermographic shot (Figure 12): assuming a stratigraphic interpretation of the wall, arise the construction phases of the ancient site works with the presence of the works of different bricklayers, made by lower rows of a material (which appears darker) probably of superior quality compared to that of the band between the recess and the window where instead the masonry is composed of smaller stone elements thus making the presence of mortar predominant. Moreover, it is interesting to note that the filling of the recess does not present any wall texture as if it had been filled entirely with a concretion material. Finally, a thermographic investigation on part of the apse wall was carried out. This portion of the church was chosen because here the coexistence of portions of plaster with parts of the masonry emerging due to the detachment of the fresco in past centuries were witnessed by the restorers. From the thermographic images, see the one in Figure 13, it appears that to date, there are no infiltrative nor detachment and disruptive phenomena of interest undermining the decorations under exam and their safeguard. Anyway, such items will be taken up in the future developments of this research campaign also considering other portions of the church and to a large extent, with reference to the works of consolidation still in progress, taking advantage of the opportunity to deepen the knowledge about the architecture.



(a) (b)

Figure 11. (**a**) One the frescoes under investigation, in particular the one near the apse. In the pictures, the reflective meter-sticks located as reference points for the subsequent post-processing are visible. (**b**) Thermal image with improved contrast in which are visible the structural peculiarities of the masonry wall, in the right corner is observable the former recess (see the cones of vision 5 and B in Figure 2).

(a) (b)

Figure 12. *Cont.*

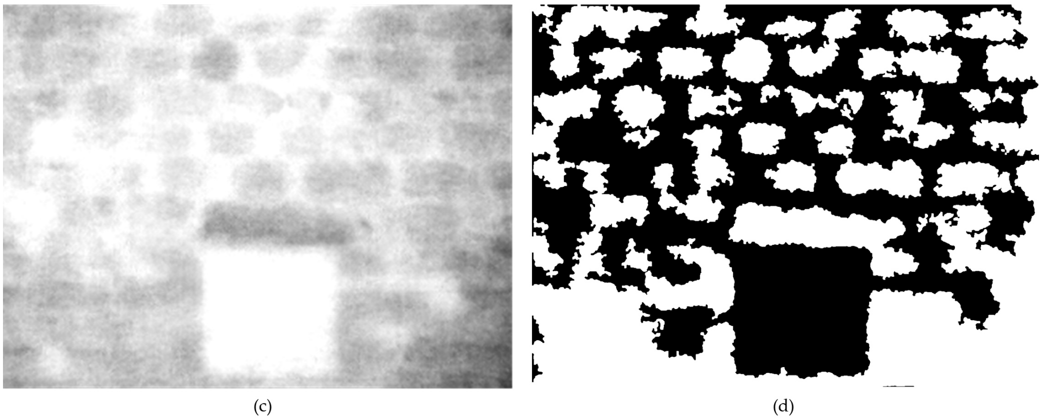


Figure 12. (**a**) Portion of the fresco under investigation, (**b**) highlighting of colours of different gradation, (**c**) thermal image with improved contrast, (**d**) final binary image (see the cones of visions 6 and C in Figure 2).

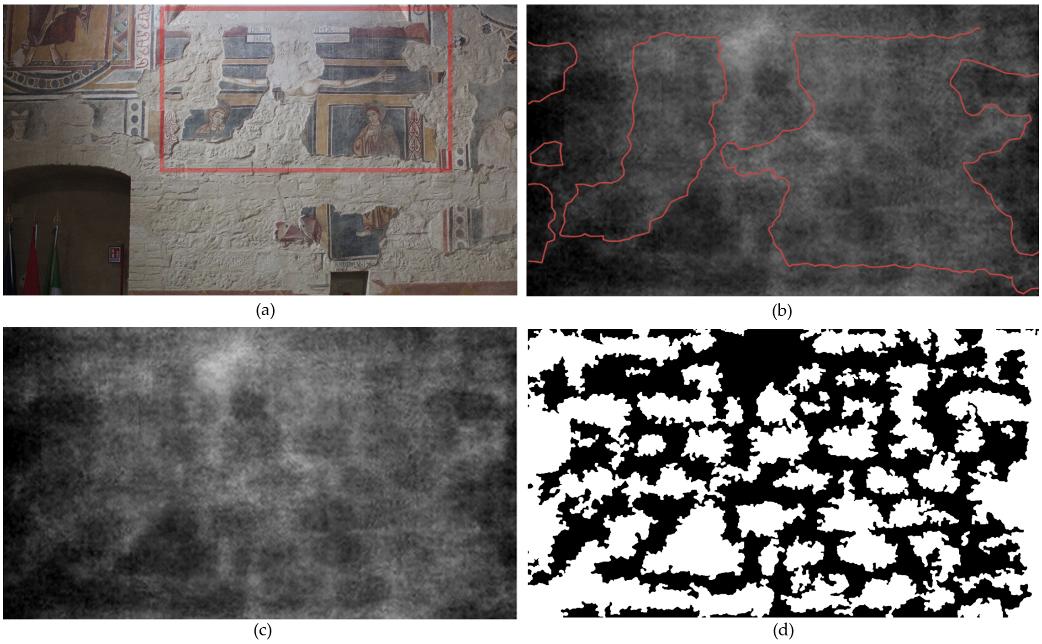


Figure 13. (**a**) Portion of the fresco under investigation, (**b**) thermal image where are highlighted in red the edges of what remains of the frescoes, (**c**) thermal image with improved contrast, (**d**) final binary image (see the cones of vision 7 and D in Figure 2).

4.5. From the Masonry Recognition to the Identification of Mechanical Properties

Non-destructive testing (NDT) techniques can be used for evaluation of mechanical properties as well as for characterization of microstructural features such as grain size, texture, nucleation, defects, deformations, or damages in various contexts, also concerning ancient masonries [27–29]. In particular, thermographic testing presents the potential to be the solution for studying masonry with both finance and time efficiency, which mainly relies on non-contact optical measurement methods in the sake of safeguard of the parietal art goods. This section discusses the evaluation of structural and mechanical properties starting from thermographic surveys. The subsequent post-processing and numerical analysis techniques are aimed at an identification of the masonry quality and typology as an a priori condition that influences the seismic vulnerability of heritage buildings.

The images obtained from thermographic surveys are used to estimate the elastic characteristics of masonry texture through the method of the test-windows [30]. This method estimates the stiffness matrix which relates the sample average of the stress vector and the average of the strain vector as follows:

$$\langle \sigma \rangle = C^{Hom} \langle \varepsilon \rangle, \tag{7}$$

where

$$\langle \sigma \rangle = \frac{1}{|\Omega|} \int_\Omega \sigma \, d\Omega, \quad \langle \varepsilon \rangle = \frac{1}{|\Omega|} \int_\Omega \varepsilon \, d\Omega \tag{8}$$

and Ω is the region occupied by the masonry sample. It is worth noting that σ and ε are the stress and strain vectors according to Voigt's notation, and assuming plane-stress hypothesis they can be written as

$$\sigma = \left\{\sigma_{xx}, \sigma_{yy}, \sigma_{xy}\right\}^T, \varepsilon = \left\{\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{xy}\right\}^T. \tag{9}$$

Therefore, C^{Hom} is a 3-by-3 matrix.

The value of the stiffness matrix C^{Hom} is estimated by applying two different sets of boundary conditions (b.c.): (i) essential b.c., where displacements are applied to the boundary of the sample, and (ii) natural b.c., where forces are applied to the boundary of the sample. In particular, in essential b.c. if displacements are applied that would induce uniform strain equals to $\varepsilon = \{1, 0, 0\}^T$ in a homogeneous material, the first column of the estimate of C^{Hom} is given by the average of the stresses, $\{C_{11}, C_{21}, C_{31}\}^T = \langle \sigma \rangle^T$, and so on. The same is true for natural b.c.: if forces inducing uniform stress equal to $\sigma = \{1, 0, 0\}^T$ in a homogeneous material are applied, the first column of the estimate of $S = \left(C^{Hom}\right)^{-1}$ is given by the average of the strain, $\{S_{11}, S_{21}, S_{31}\}^T = \langle \varepsilon \rangle^T$, and so on.

By applying essential b.c. an upper estimate of C^{Hom} is obtained, denoted C^E, while employing natural b.c. a lower estimate of C^{Hom} is obtained, denoted C^N.

As the size of the sample increases, the range between C^N and C^E decreases, and when it is sufficiently small it is assumed that the Representative Volume Element (R.V.E.) of the heterogeneous material has been obtained, with stiffness estimated by

$$C^{Hom} \approx C^* = \frac{C^N + C^E}{2}. \tag{10}$$

In the following paragraphs, the results obtained using the masonry texture shown in Figure 13 are reported, with the test-windows taken as in Figure 14.

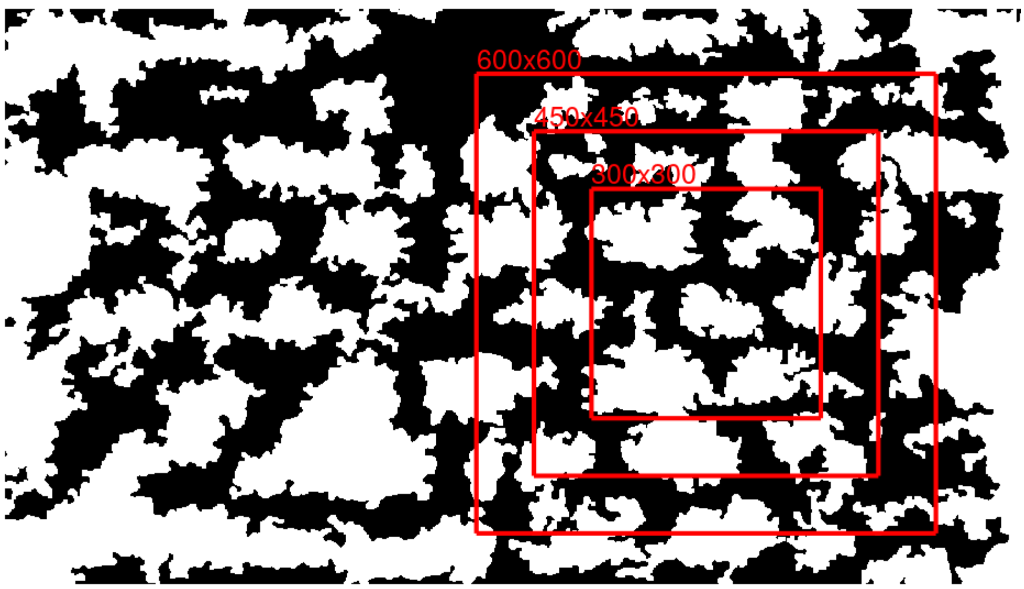


Figure 14. Test-windows used for the estimation of elastic characteristics of the masonry texture.

Three different sizes of the test-window have been used: 300 × 300, 450 × 450 and 600 × 600 pixels. It is worth noting that the software associated with the thermographic camera increases the dimension of the image with respect to the data read by the sensor from 320 × 240 pixels to 1333 × 1000 pixels. It has been assumed that the phases (the stones and the mortar) can be modelled as isotropic with a modulus of elasticity E is 15,000 MPa in stones and 1500 MPa in mortar; the Poisson's ratio is 0.2 for both phases. The problem has been solved numerically by using Finite Element Method employing four-nodes plane stress elements.

The results for the three dimensions are reported in Table 1. In the table, the penultimate row is the Frobenius norm of the stiffness matrix, while the last row is the ratio c_1 defined as the percentage of the window occupied by stones.

Table 1. Estimated of stiffness matrix for different size of test-window of the masonry sample.

Window Size	300 × 300 Pixels			450 × 450 Pixels			600 × 600 Pixels		
Estimate	C^N	C^E	C^*	C^N	C^E	C^*	C^N	C^E	C^*
C_{11}	4206.8	5245.8	4726.3	3673.8	4087.1	3880.5	3686.4	3991.8	3839.1
C_{12}	826.5	862.4	844.4	748.7	785.0	766.8	731.4	777.6	754.5
C_{22}	3677.0	4226.2	3951.6	3549.8	4109.7	3829.7	3567.1	4033.0	3800.1
C_{33}	1437.9	1761.5	1599.7	1358.7	1574.6	1466.6	1352.4	1489.1	1420.7
$\lvert C \rvert$	5886.9	7069.9	6476.6	5391.9	6109.9	5750.4	5404.9	5968.9	5686.6
c_1		0.522			0.478			0.470	

As expected, the masonry texture is weakly orthotropic, slightly stiffer in the horizontal direction, since it is almost chaotic. As can be appreciated, as the dimensions of the test-window increase a better estimate of C^{Hom} is obtained as the values for C^E and C^N converge, as it is also shown in Figure 15.

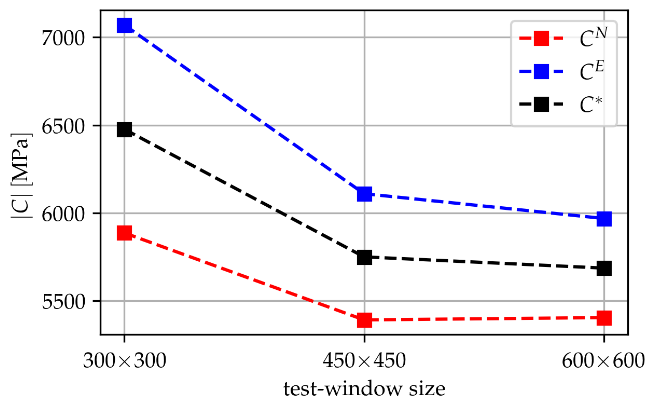


Figure 15. Frobenius norm of the estimates for C^E, C^N and C^{Hom} for different size of test-windows.

It is worth noting that the ratio c_1 changes greatly when passing from the smaller to the greater size, and this greatly affects the estimates of C.

5. Conclusions

A method in order to identify and interpret the differences of temperature in wall surfaces was proposed and applied to a real case study of great architectural value; such an approach enabled the evaluation of the historical masonry texture hidden by valuable plasters or frescoes. The procedure to elaborate the thermographic images, tuned in experimental laboratory tests, was applied to the real case of the frescoed masonry walls of the Templar Church of San Bevignate in Perugia. The obtained results highlight the reliability of this tool to identify the wall texture that is a necessary information for estimating masonry mechanical characteristics. Moreover, thermographic images are very useful to detect deficiencies and discontinuities in the wall, besides to find characteristics of the frescoes regarding their realization and actual conservation condition. Therefore, without damaging the decorations by taking essays or samples, it was possible to gain information not only on the risk factors concerning the frescoes conservation but also inherent to the safety of such historical building, closely tied to the peculiarities and stratifications of masonry, harmonizing the purpose of the safeguard of the architectural value with the basic need to evaluate the seismic vulnerability and to envisage design restoration plans. From a forward-looking perspective, since the results are promising, an extensive thermographic analysis of all the church's frescoes is being planned.

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