

Merging Nondestructive Testing Techniques for Stucco Analysis: The Case Study of St. Abbondio in Como, Italy

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ABSTRACT

Recently, a thorough preservation intervention has begun throughout the entire complex of the St. Abbondio Abbey complex in Como, Italy, beginning with documentation and condition assessment of each element of the buildings and an examination of the stucco and plaster. This article reports the results of analyses of the stuccos and plasters found in different areas of the complex. These analyses have been performed by means of infrared thermography, stratigraphic and chemical/physical testing. The results confirm the hypothesis regarding the historic evolution of the complex and supply a range of options for the preservation intervention.

Keywords: infrared thermography, stratigraphic testing, chemical/physical testing, historic preservation, architectural preservation and restoration.

INTRODUCTION AND HISTORICAL BACKGROUND

St. Abbondio Abbey is located in Como, in northern Italy. It was built in the Romanesque (late medieval) period in the place of an early Christian cruciform church. The church itself is a masterpiece of the Romanesque style, as it appears after extensive renovations undertaken in the nineteenth century. In the second half of the nineteenth century, the cloister was partially rebuilt and it now appears as an example of Classical architecture.

The complex is composed of a U-shaped building, three stories high, adjacent to the church. The church constitutes the fourth side of the inner yard. At each floor, the four facades facing the yard have a portico. The eastern and northern facades are the only investigable exteriors in the complex, because adjacent buildings were set against the other two sides of St. Abbondio (Figure 1).

The cloister lost any evidence of its medieval shape in 1834, when architect Giuseppe Tazzini modified the structure as a three-story building with arcades and columns, and it became the residence of the Seminario Diocesano Minore. A preliminary historical analysis and survey of the cloister permitted the hypothesis that an extensive part of it could easily be dated to the sixteenth century (Della Torre, 1984). A search of the historical documentation confirmed that only two sides of the cloister had been built by the middle of the sixteenth century; a major documentary clue was a list of stonecutting prices, which provided detailed information about the architectural elements in molera sandstone and dated their use in the building to 1868. Molera sandstone is a porous stone, coming from Brianza (east of Como). The stone was used for

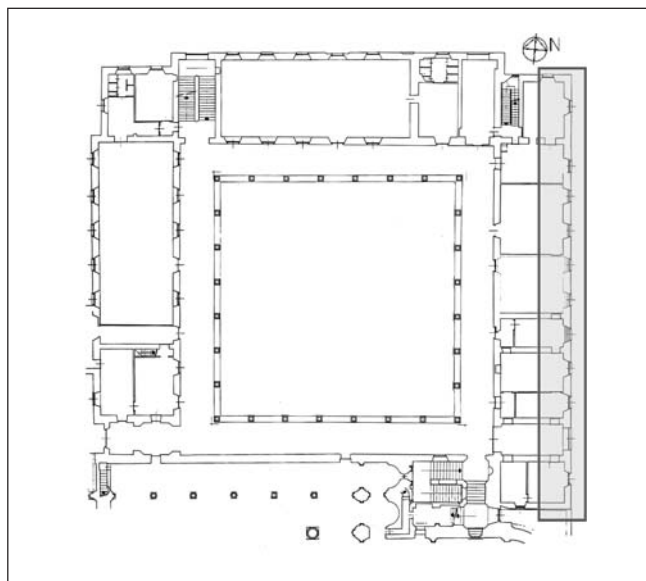


Figure 1 — Plan of the complex.

different purposes, including as a decorative stone, because of its high workability. Because of the extensive use of molera bands in the masonry throughout the complex, these elements became the reference point for dating the cloister and the exterior elevations.

Many members of the powerful Castiglioni family held patronage of the Abbey over the years, especially during the centuries in which the major refurbishments occurred. The family employed durable materials and the most highly skilled craftsmen of the time in the St. Abbondio complex.

In addition to the historic stonework, the Doric bases of the columns have a single torus (a molding at the base of a column) and gola (a molding in the cornice of the column), a phenomenon similar to that seen in the Doric cloister of St. Ambrogio, the first cathedral of Milan. These and other details have led to the St. Abbondio cloister in Como being regarded as a prominent example of Lombard architecture, alongside those buildings associated with Bramante in Milan (Della Torre, 1998).

The city of Como purchased the complex in 1974; in the following years, much intervention work has been accomplished, first in the foundations and later in the entire structure of masonry and vaults.

INVESTIGATIVE STRATEGY

Due to the complexity of the case, various historical hypotheses about the additions of the building were considered; preliminary studies, a historical analysis and a survey were performed in advance, providing enough information to plan the diagnostic phase and to develop a first level of investigation. The investigations have

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focused on two main points: detecting the boundary of the Classical building and recognizing its remains; and determining the texture of the most altered and damaged surfaces, such as the eastern facade, in preparation for the preservation project.

To clarify the project, a further analytical step was applied to the eastern facade and to some outstanding details on the first and second floors of the inner cloister; moreover, some rooms and the main staircase in the eastern part of the complex have been investigated to find the correspondences between the historical evidence discovered on the exterior and the evidence found inside the building. Stratigraphic samples showed a high number of overlaying plasters and revealed their sequences in many areas of the building; knowing the time sequence of the coatings, tints and fading, it has been possible to systematically order and connect the material findings, which were occasionally discovered during the restoration.

Infrared thermography supplied a preliminary map of the invisible irregularities of the eastern facade. The mosaics of the infrared thermograms showed the walled up openings beneath the coatings and the areas where the thermal properties of the stucco were inhomogeneous.

Through the historical, visual and infrared analyses, many architectural elements were specifically dated to the Romanesque period, the Renaissance or the nineteenth century. Laboratory analyses of the stucco, plaster and mortar samples, on the other hand, have been focused on grouping samples according to composition.

X-ray diffraction, porosimetric analysis, thin section microscopy and atomic spectroscopy have been applied on stuccos, plasters and finishing samples. The results support the comparison of the morphological, chemical and physical parameters and permit grouping the samples with similar components and properties (such as the presence of Portland cement as a binder), assuming that the mortars with similar features correspond to similar historic phases.

The location of the grouped samples permits the verification of the hypothesis regarding the evolutionary phases of the complex, because their sequence indicates the relative chronology of their overlapping and permits the evaluation of the chemical and physical compatibility among the different coatings. The comparison of the results with the archival documents permits us to construct the chronology of the historical interventions.

METHODS AND MATERIALS

Infrared Thermography

Infrared thermography has been extensively used on the eastern facade to obtain data regarding the masonry's texture beneath the plaster and to map the inhomogeneity of the coatings (Figure 2). The

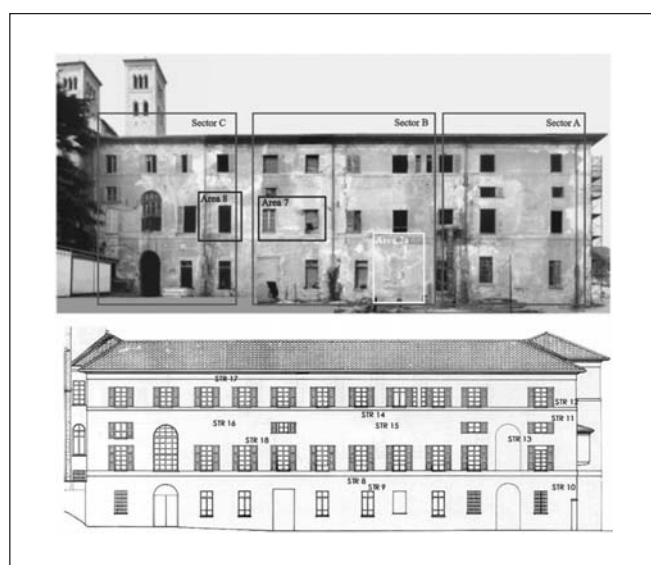


Figure 2 — The eastern elevation, location of the infrared thermography investigation and the stratigraphy tests: (a) photograph with areas of investigation shown; (b) schematic of the same.

surface is constituted by an inhomogeneous stucco: many stains, crusts and mold spot the surface, delaminations and cracks are diffused and the masonry is revealed by localized breaks in the stucco.

Active infrared thermography enables specific subsurface layers to be analyzed in detail, but the heating to be applied and the time for measurement must be determined precisely (Rosina et al., 2002). Moreover, the condition of the surface can seriously affect the signal coming from it, because during irradiation these differences can cause differentials in local absorption rates and consequently an uneven heat flow inside the structure. In addition, these surface irregularities are the main filter of any thermal signal emanating from inside the structure.

Nevertheless, in the preliminary phase of the analysis, the expected results are mostly qualitative and the main goal is to map the most evident discrepancies between visual and infrared observation. At this stage, even a qualitative comparison between the infrared and the visual images can be effective in reducing false alarms. In the case of St. Abbondio, the passive approach was successful in obtaining the required readout of the substrate.

The extension and orientation of the elevation obliged us to exclude any artificial source for stimulating the surface under investigation. The orientation of the facade is east-southeast: the elevation does not receive a homogeneous irradiation due to its length (greater than 36 m [120 ft]) and its orientation. Nevertheless, the heating can be compared within vertical strips, in which it is possible to subdivide the entire elevation for localized analysis.

In order to reduce the effects of the uneven heating resulting from colors, material decay and orientation, the best heating condition resulted in a diffused radiation, as when radiation is filtered through a thick layer of clouds. Additionally, the air's thermal gradient due to the daily thermal excursion (10 K [18 °F] between the night and 11:00 a.m., when the tests ended) caused a convenient convective heating of the surface, due to the warmer air coming into contact with the surface. Experience with historic building surfaces (Ludwig and Rosina, 1997; Bison et al., 1996) suggests that the comparison of repeated shots, between the beginning of heating and the cessation of cooling, dramatically improves the effectiveness and reliability of thermal analysis. The standardized dynamic procedures for industrial applications are hardly feasible in the preliminary phase of the analysis (Rosina and Robison, 2002), when the thermal properties of the investigated materials are unknown, the section of the masonry under analysis can frequently only be roughly drawn and the surface under investigation is extensive. Nevertheless, the qualitative comparison of the repeated scans permits us to ignore those discontinuities resulting from exterior surface problems which are not of interest to this investigation. In the following, we report only a few images showing the most significant discontinuities detected in the scanning at 8:00 and 10:00 a.m.

Stratigraphy

Infrared thermography permitted us to locate the thermal discontinuities which were supposed to be indicative of the researched ones. In those areas, further investigation was performed in order to determine the sequence of the layers composing the coating and, where possible, to verify the components of the masonry and its texture. The emerging layers were compared with those discovered in other parts of the buildings and the comparisons helped to reinforce or diminish the validity of the historical hypotheses about the evolution of the complex. Moreover, from these layers some microsamples were collected to be analyzed in the laboratory, in order to validate the results of infrared thermography and stratigraphy.

In the eastern elevation of St. Abbondio, 11 stratigraphic tests have been performed. The stratigraphic technique consists of scraping the surface from the exterior layer towards the inner part of the coating, as far as the substrate. The operator leaves a small square of each layer visible, before continuing to scrape the underlying layer. The result is a sequence of smooth and thin steps, at least one for each discovered layer (Feiffer, 1997; Montagni, 2000; CNR-ICR, 1980; CNR-ICR, 1985; UNI, 2001). The most significant results are reported below, as examples of the method of investigation.

Chemical/Physical Analysis

Samples were collected from the cloister, the interior and the exterior elevations. The historical information mostly regards the cloister and, for that, it was possible to date the layer sequence of stucco and the stone decoration of its wall. In absence of specific archival documentation regarding the refurbishments of the eastern facade, the researchers confirmed the sequence of the evolutionary phases of the eastern elevation by comparing the samples collected from the eastern facade and the cloister.

Porosimetric analyses have been carried out on samples of 1 cm³ (0.6 in.³) with two mercury porosimeters: one to determine macropores with radii between 7.5 mm and 3.7 μ m (0.3 and 1.5 $\times 10^{-4}$ in.) and another to determine megapores with radii between 50 and 1 mm (2 and 0.04 in.).

Other forms of analysis were also undertaken. In petrographic analysis, thin sections of samples were observed using a standard microscope in polarized light. X-ray diffraction tests were also performed, with powdered samples analyzed by a diffractometer equipped with a goniometer.

Metallic analysis was carried out as follows: a weighed amount of dried mortar samples were treated with 1 N hydrochloric acid and ultrapure water. The suspension was stirred at room temperature for 2 h, filtered on a round fiberglass filter measuring 0.25 mm (9.8 $\times 10^{-3}$ in.) and the residue accurately washed and weighed. The solution was then transferred into a volumetric flask and analyzed. Iron and aluminum were determined by atomic absorption spectroscopy with electrothermal atomization, while silicon, calcium and magnesium were detected by inductively coupled plasma-optical emission spectroscopy. The analytical lines used for the determination of the atomic absorption spectroscopy with electrothermal atomization were 248.3 nm (9.7 $\times 10^{-6}$ in.) for iron and 309.3 nm (1.2 $\times 10^{-5}$ in.) for aluminum. Inductively coupled plasma-optical emission spectroscopy spectral lines were 393.4 nm (1.5 $\times 10^{-5}$ in.) for calcium, 279.5 nm (1.1 $\times 10^{-5}$ in.) for magnesium and 252.4 nm (9.9 $\times 10^{-6}$ in.) for silicon.

Table 1 shows the samples with their labels, a brief description and the area of provenance.

Table 1 The samples with descriptions and provenance

Sample	Description and Provenance
1	White plaster sampled under the floor level
2a	Pink plaster at the back of a concrete beam
2b	Plaster; same position as 2a; 1 m (3.3 ft) above and to right
2c	Plaster; same position as 2b; lower level
3	Plaster of the vault corbel
4	Plaster with many color-wash paintings
5	Hammered plaster; sampled at the same sample of 4
6	Plaster; smoothing higher than sample 5; rough texture and diffused white lumps; external layer
7a	Plaster; external front; sampled from hammered lower layer
7b	Plaster, external front; sampled from smoothing (upper external layer)
8a	Plaster; external front; sampled from hammered lower layer
8b	Plaster; external front; sampled from smoothing (upper external layer)
9	Plaster; external front; sampled from hammered lower layer
10	Plaster; external front; sampled from hammered lower layer

RESULTS

Infrared Thermographic Results

The first thermal scanning took place at 8:00 a.m., after 30 min of diffused irradiation. Air temperature was 291 K (64 °F), with a relative humidity of 56%. The thermograms were shot while the thermal gradient between the outdoors and inside was 8 K (14 °F) and was increasing. The heat flux flowing across the structure permitted us to locate the thermal bridges crossing the entire thickness of the structure, such as the filled opening.

Referring to the figures, in area 1, below the molding at the higher

floor, a colder band is detectable; in the visual analysis, the surfaces are much more discontinuous than is visible through the infrared tests, but the spots do not correspond between visual and infrared. The thermal discontinuities indicate the presence of a material with a higher thermal inertia in the masonry beneath the stucco. The archival research confirmed the use of the molera stone bands in the facade and the location was confirmed by infrared thermography, helping to date that part of the elevation to 1868.

In area 2, the sealing of six ancient openings appears through the infrared testing; the shape of the arches is clearly detectable — they are not axial to the current windows. At the first floor, the extension of the walled up fenestration is wider than the current ones. At the ground floor in sector B (Figure 3, area 2A) another walled up opening is clearly detectable, while at the higher floor, only a few traces of previous opening can be localized because of the repeated opening and restructuring of the masonry. Additional information can be found in Figure 4, area 3.

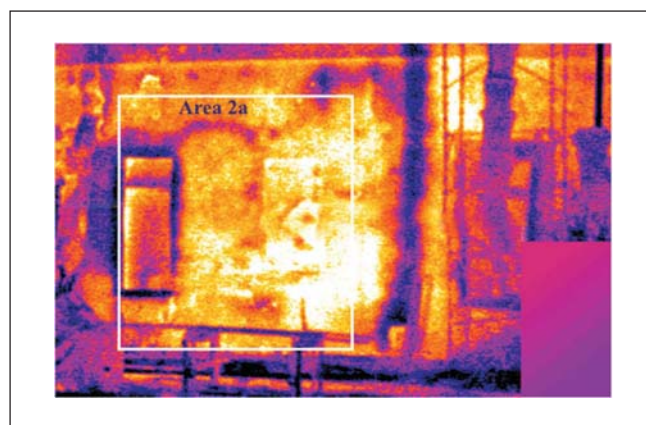


Figure 3 — Mosaic of sector B; range of temperature = 291.8 to 293.1 K (65.6 to 67.9 °F); emissivity = 0.92.

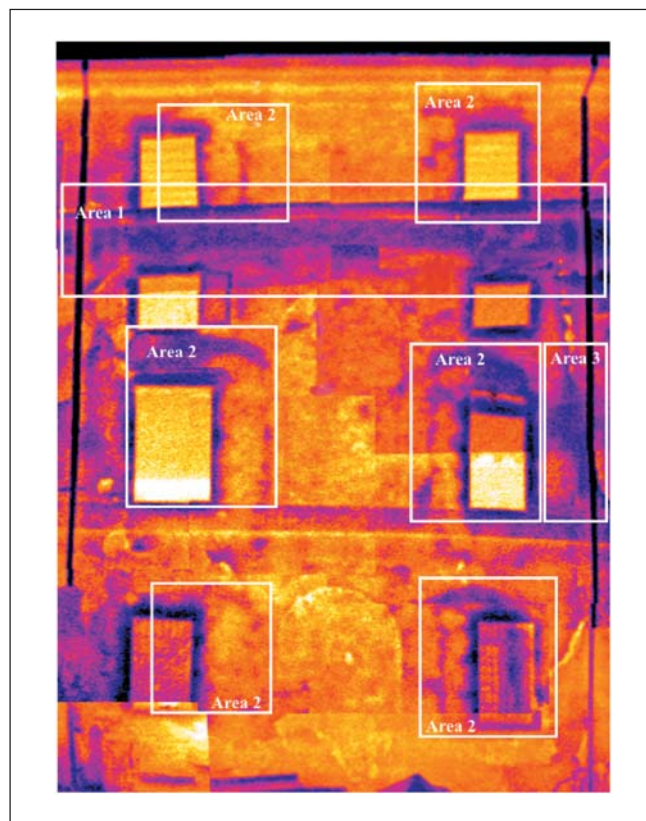


Figure 4 — Infrared thermographic mosaic of sector A; range of temperature 292 to 293.5 K (65.9 to 68.6 °F); emissivity = 0.92.

The infrared thermography shows large colder areas corresponding to water infiltration, which is extensive in the stucco; it probably originated through the holes disseminated throughout the stucco, the nearby descending pipe and the ruined eaves' canalization at the eastern corner. Figure 5 shows a chimney's shape spanning the building from the ground floor to the higher levels of the building.

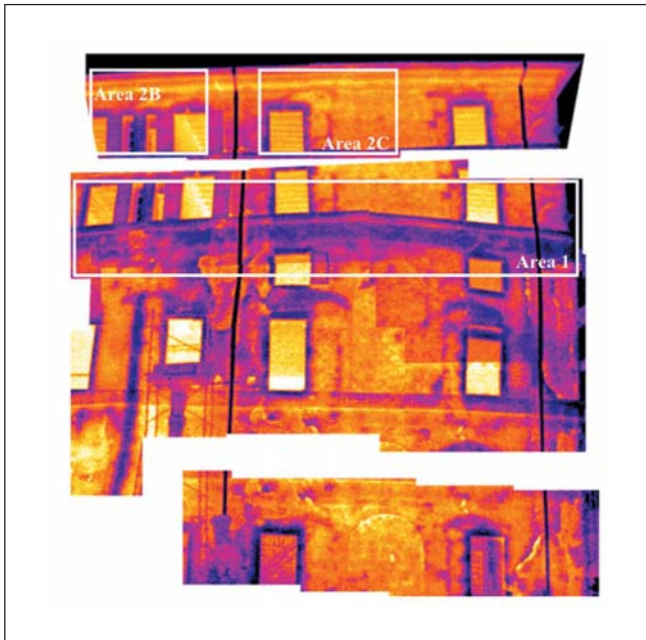


Figure 5 — A chimney's shape is clearly localized from the ground to the higher floor of the building; the thermal images show that the shape and the extension are constant on the whole façade.

The second thermal scanning took place at 10:00 a.m. Air temperature was 294 K (70 °F), with a relative humidity of 45%. After 2.5 h of diffused irradiation and 600 s of direct solar irradiation, the texture of the masonry can be read in the zones where the stucco is homogeneous, adherent to the masonry and thinner than 20 mm (0.8 in.), as shown in Figure 6 in a transient condition (first phase of cooling).

In area 1, the diffusion of the heating inside the structure due to the lasting thermal stimulation does not allow us to localize the discontinuity previously detected. In areas 2, 3, 4 and 6, through the thickness of the stucco, infrared thermography permits us to detect the texture of the wall. Small and irregular stones constitute the masonry. A warmer line draws the edge of the thicker 8.4 mm (0.3 in.) stucco surrounding the filled opening.

In area 5, the thermal images show stretched courses, a texture similar to areas 2 and 6, although the higher discontinuities of the surface affect the readability of the structure.

At the ground level and first floor, the texture of the large arches reassembles to the structure of areas 2 through 6, nevertheless details of the left and right edges show that the masonry of the blinded arch and the surrounding masonry does not have aligned stretched courses.

Stratigraphic Results

Stratigraphic testing of area 1 revealed that the greyish stucco (sample 11) is 12.7 mm (0.5 in.) thick and coats a masonry composed of bricks stretched across and a double thick section of molera stone, which corresponds to the colder strip localized by infrared thermography. In sample 12, below the molera segment, there appears a carved cornice about 32 mm (1.25 in.) high. The thickness of the stucco is higher upon the molding, as it was set before the rising of the last floor.

Stratigraphic testing of area 2 (sample 13) revealed that the stucco is thinner inside the blinded arch than in the rest of the

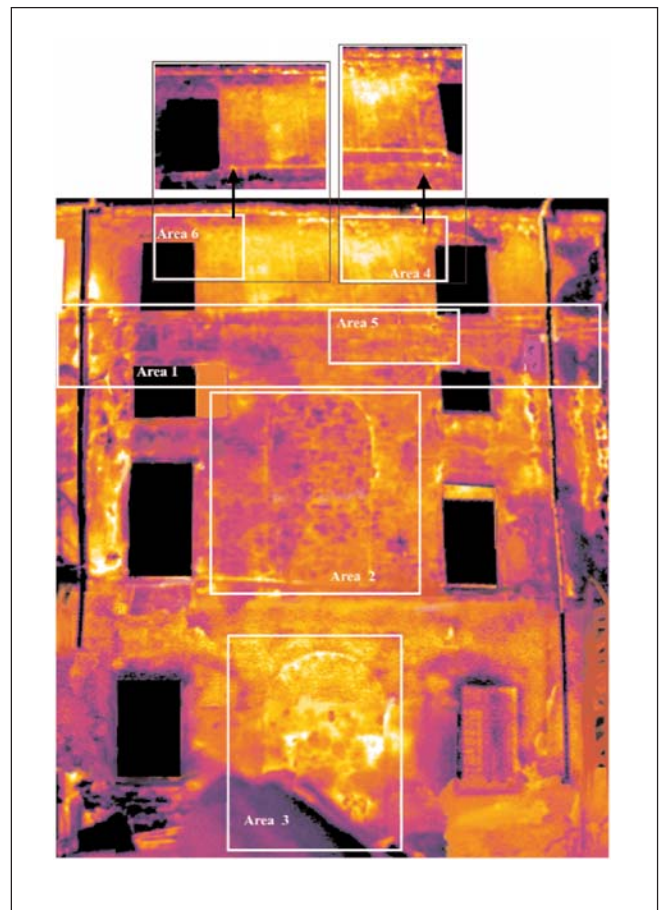


Figure 6 — Areas 1 through 6, showing a range of temperature from 295.4 to 298.5 K (72 to 77.6 °F); emissivity = 0.92.

wall, differing by about 8 mm (0.3 in.). Underneath the greyish stucco and an inner layer of pinkish stucco 6 mm (0.25 in.) thick, the moltrasio stone ashlar appear; the edges of the quoins correspond to the shape of the large arch and actually reveal the walling up of a previous fenestration (Figure 7). (Moltrasio stone is a well stratified limestone, sometimes dolomitic, coming from the lake shore north of Como. The stone was used as building stone or as slabs for roofing, but its use as cut stone was negligible.) Although the infrared thermography did not detect a difference in the masonry's texture

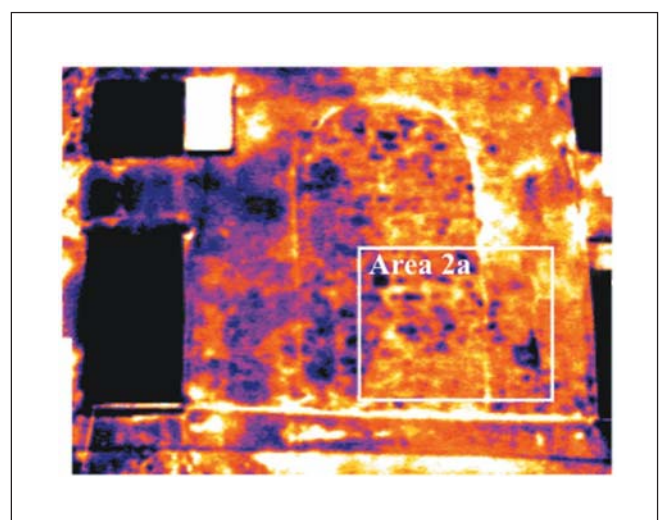


Figure 7 — Infrared thermography at 10:00 a.m., sector A, area 2.

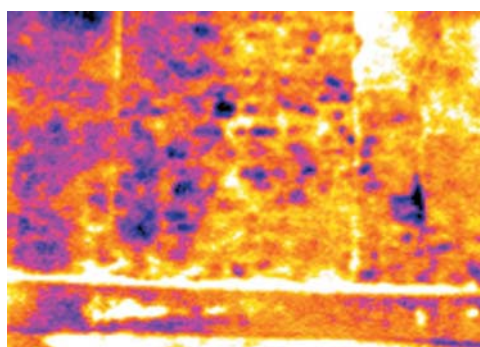


Figure 8 — Detail of infrared thermography of area 2 shown in Figure 6.

between the infilling and the masonry, the courses of the quoins are interrupted at the perimeter of the infilling (see Figure 8, a detail of Figure 6 at the first floor). The same result could be expected at the ground level, where the shape of another arched opening is marked in the stucco. Unfortunately, the surface damage affects temperature distribution, making infrared thermography ineffective in detecting the texture of the blinded arch. Direct comparison between the infrared thermographic images of the two areas is not reliable (see Figure 3, area 3).

Infrared thermography of sample 9 reveals the shape of an arched opening underneath the stucco in area 2a. The stratigraphy confirms that the greyish layer of stucco 25 mm (1 in.) thick coats the bricks of an arch.

Chemical Testing Results

Results of thin section observations, porosimetric and X-ray diffraction testing are summarized in Table 2. As regards the mineralogical, morphological and physical features, samples have been grouped as follows:

- group 1 (samples 1, 2a, 2b, 4 and the inner layer of 2c)
- group 2 (the external layer of sample 2c)
- group 3 (sample 3)

Table 2 Synoptic table of X-ray diffraction and porosimetric results as well as thin section observations

Sample	Binder	Texture	Cavities	Aggregate	Sorting	Binder/Aggregate Ratio	Total Porosity	Maximum	Group
1	lime	big lumps	absent	quartz/silicates	medium/ good	3:2	30.8%	2 to 5 mm (0.08 to 0.2 in.)	1
2a	lime	homogeneous	rare	silicates from metamorphic rock	medium/ scarce	1:1	29.7%	0.1 to 0.3 mm (0.004 to 0.01 in.)	1
2b	lime	homogeneous	rare	quartz/plagioclase biotite	good	3:2	30.2%	2 to 5 mm (0.08 to 0.2 in.)	1
2c inner	lime	homogeneous	absent	silicates	medium/ scarce	3:2	31.7%	0.1 to 0.2 mm (0.004 to 0.008 in.)	1
2c outer	lime	lumps	absent	limestone	scarce	1:1	31.7%	0.1 to 0.2 mm (0.004 to 0.008 in.)	2
3	lime	spongy	diffused, fissure lattice	silicates, quartz and limestone	scarce	3:1	25.2%	0.1 to 0.2 mm (0.004 to 0.008 in.)	3
4	lime	big lumps	diffused	quartz, silicates	scarce	3:2	32.6%	2 to 5 mm (0.08 to 0.2 in.)	1
5	lime	small lumps	diffused	plagioclase, quartz, limestone	good	2:1	33.0%	0.5 to 1 mm (0.02 to 0.04 in.)	4
6	lime	big lumps	diffused	quartz, silicates, limestone, dolostone	scarce	not detectable	28.3%	2 to 5 mm (0.08 to 0.2 in.)	5
7a	lime	big lumps	diffused	quartz, silicates, limestone, flint	scarce	3:1	35.2%	0.1 to 0.2 mm (0.004 to 0.008 in.)	4
7b	lime	big lumps	diffused	quartz, silicates, limestone, flint	good	3:1	30.2%	2 to 5 mm (0.08 to 0.2 in.)	6
8a	lime	big lumps	diffused	quartz, silicates, limestone, flint	scarce	3:2	35.7%	0.2 to 0.3 mm (0.008 to 0.01 in.)	4
8b	lime	lumps	diffused	quartz, silicates, limestone	good	3:2	31.0%	2 to 5 mm (0.08 to 0.2 in.)	6
9	lime	small lumps	scarce, fissures	quartz, silicates, limestone, flint, dolostone	scarce	2:1	34.3%	0.2 to 0.3 mm (0.008 to 0.01 in.)	4
10	lime	lumps	scarce, fissures	quartz, silicates, limestone, flint, dolostone	scarce	3:1	34.4%	0.2 to 1 mm (0.008 to 0.04 in.)	4

- group 4 (samples 5, 7a, 8a, 9 and 10)
- group 5 (sample 6)
- group 6 (samples 7b and 8b).

Binder was an ineffective classifier because all of the samples contained the same kind of binder, lime. However, the aggregate composition enabled us to separate group 1 (of silicatic composition) and group 2 (of calcareous composition), from the other samples, which are characterized by a mixed composition. The sand used in mortar aggregates has different provenance depending on its composition: silicatic sand comes from the sediments of the Adda River in northern Como Lake (outcrops of igneous and metamorphic rocks); mixed composition sand comes from sediments of southern Como Lake (glaciofluvial deposits and limestone outcrops). Calcareous sand is especially selected for the external layer of plasters, as in Vitruvius's recipe.

As shown in Table 2, group 1 is also characterized by high thickening. Sample 3 is the only one which shows fissure lattices as cavities.

Porosimetric values are highly homogeneous in group 1 and in group 2.

As far as chemical composition is concerned, all of the samples are similar except for the calcium content. Samples 1 and 6 show calcium contents much lower than the other samples, as illustrated in Figure 9. As calcium compounds represent most of the soluble fraction, the percentage of acid soluble content followed the same trend (Figure 10).

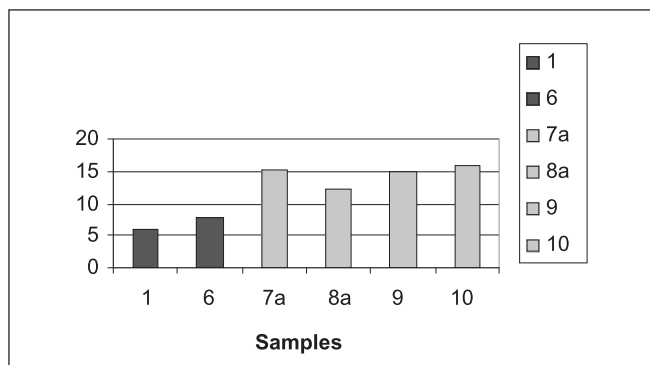


Figure 9 — Calcium content (weight percentage).

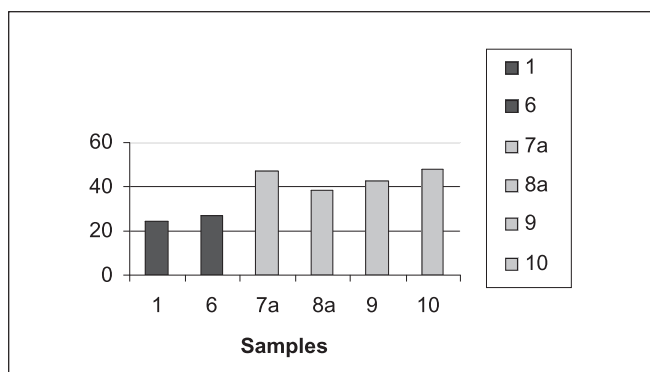


Figure 10 — Acid soluble content (weight percentage).

The percentage of acid soluble content was calculated as follows (Dupas and Charola, 1986):

$$(1) \quad ASC = \frac{100 (W_m - W_a)}{W_m}$$

where

ASC = the percentage of acid soluble content

W_m = the weight of the dried mortar sample

W_a = the weight of residue after acid attack and wash.

Moreover, the results (as weight percentages of samples, of residue after acid attack and of acid soluble content) were determined by chemometric testing (principal component analysis). The principal component analysis plot clearly pointed out the differences between the samples and showed two different clusters: samples 8a, 9, 10 and 7a in one group and 1 and 6 in another.

The sample composition shown by atomic spectroscopy and the chemometric elaboration of data confirmed the classifications shown in Table 2 and discussed above.

DISCUSSION OF THE RESULTS

Merging the results of the survey, historical analysis, infrared thermography, stratigraphy and chemical/physical analysis, the most significant indication came from area 2. In area 2, sample 13, the presence of the double stucco layer indicates that the closure of the opening was accomplished before the last refurbishment of the facade, that is, before the rising of the last floor and the final greyish pargetting.

In sample 9, the validation of the presence of this filled opening allowed us to obtain a key factor for the thermal analysis of the entire elevation: the areas in which the temperature distribution shows the same pattern of area 2 correspond to filled fenestration and they serve as a reference area in the comparison between the thermal discontinuities detected by infrared thermography. Observing Figures 3 and 4, it is possible to notice a high number of walled up openings: their shapes, dimensions and locations are quite different, many of them not being aligned on the same vertical axis. The information assumes high priority for the structural analysis of the building, because the mosaic of the thermal images, validated by the stratigraphic tests, permits us to identify the actual untouched section of the wall and to evaluate the corresponding vertical distribution of the loads. Additionally, sample 18 confirmed the presence of another filled opening. Despite the inhomogeneous heating of the facade, a qualitative comparison with the reference area permitted us to locate the filled fenestrations even if the thermal gradient between the filling and the rest of the surrounding masonry was lower than in the reference area.

Moreover, the lab tests show that the stucco beneath the current one on the eastern elevation (groups 4, 5, 7a, 8a and 10) has the same characteristics of sample 5 in the cloister. Because of the absolute dating of the evolution of the cloister, it is possible to use that date (during the 16th century) to date the stucco samples from the eastern elevation of the same group (number 4).

Samples 7b and 8b are grouped as number 6, and they correspond to the external layer, the current stucco due to the last refurbishment. The sorting of this layer is better than for the one underneath (group 4, 19th century).

The composition affinity of some samples and their position inside the stratigraphic sequence allows us to state that large zones of sixteenth-century stucco are still standing on the facade of the building. The lab tests determined that the stucco is composed of lime mortar, quite compatible with the ancient plasters underlying them; the condition of these surfaces, however, is not satisfactory for exposing the inner, original layers to air pollution and weather.

Indication for the Preservation Project

The testing performed provided useful data to support the reintegration of missing stuccos with a new one, guaranteeing the chemical and physical compatibility.

As far as binders are concerned, the first layer adjacent to the masonry was made of natural hydraulic lime without any water soluble salt; the second layer and finish were made of seasoned lime stucco.

Finally, two chromatic solutions were provided which were compatible with the layers of stucco and which could be applied to both the original stucco and the restored one: the colors for lime-wash and the potassium silicate colors. Because of their higher weather resistance, in particular to surface scour, the latter are preferable for extensive and eastward oriented elevations, such as the investigated facade.

CONCLUSION

The results confirmed the historical hypotheses about the evolutionary sequence of the building phases, demonstrating that this kind of analytical investigation is valid in support of preservation projects.

The integration between qualitative tests, based on the multi-spectral images (visual and infrared) and the quantitative analysis (chemical/physical lab tests) overcame the limitations due to the lack of absolute values of the qualitative methods and the narrow field of application of the quantitative results (any value is specific of each analyzed sample and it can be extended to a larger area only if the images confirm the homogeneity of the surface under investigation). Moreover, the key factor for the success of the investigation was the close collaboration between those experts on different subjects. From the planning of the tests to the common discussion of the results coming from the different methods of analysis, the collaboration allowed us to obtain the mutual validation of the results and to increase the effectiveness of any one technique, overcoming the limitations of each specific method.

The present experience regarding the integration of NDT in this type of work is evidence that historians can dramatically improve their hypotheses, that restorers can reduce the risk of performing incompatible work and, above all, that it is possible to avoid the unintentional loss of historic materials. The costs of the preliminary study and analysis are a necessary investment for avoiding more expensive changes when the preservation project has already begun.

REFERENCES

- Bison, P., M. Dezzi Bardeschi, E. Grinzato, E. Rosina, T. Kauppinen and G. Tucci, "Infrared Thermal Scanning as a Methodology for Survey of Façades Palazzo della Ragione, Milan, Italy," *Proceedings of Thermosense XXIV: An International Conference in Thermal Sensing and Imaging, Diagnostic Applications*, Orlando, Florida, 1996.
- CNR-ICR, *Norma 3/80, Campionamento di materiali in opera e conservazione dei campioni*, Rome, CNR-ICR, 1980.
- CNR-ICR, *Norma 20/85, Interventi conservativi: esecuzione e valutazione preventiva*, Rome, CNR-ICR, 1985.
- Della Torre, S., "Note sul chiostro di S. Abbondio," *S. Abbondio lo spazio e il tempo: Tradizione storica e recupero architettonico*, Como, Italy, 1984, pp. 309-326.
- Della Torre, S., "Il cantiere della Cattedrale e l'architettura del Rinascimento a Como," in *Le arti nella diocesi di Como durante i vescovi Trivulzio*, M.L. Casati and D. Pescarmona, eds., Como, Italy, 1998, pp. 23-33.
- Dupas, M. and A.E. Charola, "A Simplified Chemical Analysis System for the Characterization of Mortars," *Proceedings of the Second International Colloquium on Materials Science and Restoration*, Esslingen, Germany, 1986, pp. 309-312.
- Feiffer, C., *La conservazione delle superfici intonacate, il metodo e le tecniche*, Skira, Milano, Italy, 1997.
- Ludwig, N. and E. Rosina, "Heat Transfer Models for Detecting Deep Structures in Masonry," *Proceedings of the Fourth International Workshop on Advanced Infrared Technology and Applications*, Firenze, Italy, 1997.
- Montagni, C., *Materiali per il restauro e la manutenzione*, Utet Torino, Italy, 2000.
- Rosina, E. and E. Robison, "Applying Infrared Thermography to Historic Wood-framed Buildings in North America," *APT Bulletin*, Vol. 33, No. 4, 2002.
- Rosina, E., E. Robison and E. Grinzato, "Mapping Masonry Bonding by Quantitative IR Thermography," *Proceedings of Thermosense XXIV: An International Conference in Thermal Sensing and Imaging, Diagnostic Applications*, Orlando, Florida, 2002.
- UNI, *Norma UNI 10945/2001, Beni culturali: caratterizzazione degli strati pittorici e generalità sulle tecniche analitiche impiegate*, Milan, UNI, 2001.